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THE SMOKE PROBLEM OF GREAT CITIES

The Soot-fall in a Minute within the County of London and a Londoner on the Same Scale.

From a model in the exhibit of the Ministry of Health at the British Empire Exhibition, 1924–25.

Frontispiece.

THE SMOKE PROBLEM OF GREAT CITIES

BY

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PREFACE

Much of the work which is represented by the pages of this volume has been done with a view to successive reports of a Committee for the Investigation of Atmospheric Pollution, appointed in 1912 in order to give effect to the wishes of a conference held in London in connection with a smoke-abatement exhibition in that year.

The committee was purely voluntary ; originally it relied to a considerable extent upon the good offices of the *Lancet*, which had not only facilities in regard to publication but also a laboratory which was then in charge of the late Mr. S. A. Vasey, himself a member of the committee. He was very helpful in finding a way through the difficult questions of the chemical analysis of the large bottles of dirty water which represented a month's material for investigation. The other active members of the committee were Dr. Des Voeux, treasurer of the Coal Smoke Abatement Society, Mr. J. G. Clarke, F.C.S., Dr. R. Lessing, F.C.S., all of London, Mr. J. B. C. Kershaw, of Manchester, and Bailie W. Smith, of Glasgow.

Some of these names were already well-known, and have now become still better known, in connection with the smoke problem of great cities, but the question referred to the committee was limited to the investigation of the amount and nature of atmospheric pollution "for its own sake," to adopt a phrase that, by long use, has acquired a sort of scientific implication. The reader must therefore exonerate our colleagues on the committee from responsibility for anything outside the limits of purely scientific inquiry which may be found in these pages.

The first reports of the committee were published by the *Lancet* as a private enterprise ; but when the means of collecting and analysing atmospheric impurity had been

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formulated and more definite organisation became necessary, a grant of £500 a year was obtained from the Department of Scientific and Industrial Research, for the publication of reports and for incidental expenses, on condition that the Meteorological Committee, which at that time controlled the work of the Meteorological Office by appointment of H.M. Treasury, should accept responsibility for the expenditure of the grant. The committee was accordingly brought into official relations with the Meteorological Office as an Advisory Committee on Atmospheric Pollution, upon which the department had a representative, originally Mr. W. S. Curphy, and subsequently Dr. Margaret Fishenden.

Opportunity was taken at the same time to invite municipal and other local authorities who took part in the investigation to nominate representatives on the committee, among whom Dr. Ashworth, of Rochdale, Dr. Cates, now of Kingston-on-Thames, Dr. Haldane Gee, of Manchester, Dr. Simpson, of Newcastle, and Mr. A. R. Tankard, of Hull, have been specially helpful, in addition to Bailie W. B. Smith, who became the representative of Glasgow. The Ministry of Health has also nominated a welcome representative in the person of Dr. T. L. Bailey.

In addition to the advantages which have been enumerated, the grant by the Department enabled the committee to employ a graduate of the Imperial College of Science and Technology as a scientific assistant; and through the good offices of Professor H. B. Baker, F.R.S., also a member of the committee, their assistant was enabled to use a room in the college as a laboratory. This was of inestimable value to the investigation, the more so as the assistant, Mr. G. M. Watson, proved himself, in spite of precarious health, to be a very competent physical chemist and an enthusiastic worker. To the deep regret of all with whom he was associated, his health failed in November, 1924, and in April, 1925, he died.

His illness and death have proved to be a severe blow to the prosecution of the inquiry. When the Meteorological Committee, and the Office which it controlled, were incorporated in the Air Ministry in 1919, the work of the Advisory Committee on Atmospheric Pollution came to be regarded

as part of the duty of the Meteorological Office subject to the same financial conditions and regulations as any other part of that duty ; and, in accordance with the regulations, the Advisory Committee lost all claim to the services of an assistant during Mr. Watson's illness and the use of the laboratory after his death. The programme for the future is even now in suspense.

It was the practice of the Advisory Committee to refer the details of its scientific work to what was known as a technical sub-committee. In that way the authors have had the opportunity of scientific consultation of a very productive kind with experts in the various departments of science upon which the investigation of atmospheric pollution depends. Personally, therefore, we owe a special debt of gratitude to Mr. J. G. Clarke, Mr. J. H. Coste, Professor J. T. MeGregor Morris, Mr. L. F. Richardson, Mr. F. J. W. Whipple and Mr. J. W. Walsh.

Under the arrangements of the Air Ministry, the more recent reports of the committee were published by H.M. Stationery Office. Some of the text and many of the illustrations of this book are taken from the reports. Figures 12, 13 and 32 are from the seventh ; figures 17, 25, 26, 31, 34, 35, 39, 42, 47 from the eight ; figures 27, 36 to 38, 40, 41, 43 to 46 and 49 from the ninth ; figures 28 to 30 and 53 are from the tenth report. We acknowledge with thanks our obligation to the Controller of the Stationery Office for permission to use the text and illustrations of the reports. A similar acknowledgment is also due to Dr. G. C. Simpson, Director of the Meteorological Office, not only for his concurrence in that permission, but also for assistance in many other ways in the promotion of the inquiry.

NAPIER SHAW.
JOHN S. OWENS.

London,
September 14, 1925.

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IN CASE WE FORGET:

THE MEANINGS OF CERTAIN TECHNICAL TERMS AND ABBREVIATIONS.

A MICRON (μ) which is used for measuring dust particles is 1/1000 of a millimetre (mm.) or 1/25400 of an inch.

The wavelength of violet light is 0·40 micron.

The wavelength of red light is 0·67 micron.

The wavelength of 5XX (Daventry) is 1600 metres or 1,600,000,000 microns.

1 decimetre (dcm.), a tenth of a metre, is approximately 4 inches.

1 square centimetre (cm.^{2}) is 0·155 square inch.

1 square metre (m.^{2}) is 10·764 square feet.

1 square dekametre (10m.^{2}) is 100 square metres.

1 square kilometre (km.) is 0·386 square mile.

1 metric ton (tonne) per square kilometre is 2·56 tons per square mile, or 9 lb. per acre.

1 metre per second (m/sec.) is 2·24 miles per hour.

1 metric ton is 2205 lb.

1 cubic inch. (cu. in.) is 16·387 cubic centimetres (c.c.).

1 cubic metre (m.^{3}) is 35·317 cubic feet.

1 litre (l.) is 1000 cubic centimetres, 0·22 gallon, 0·03531 cubic feet.

1 gramme (g.) is 15·432 grains.

1 milligramme (mg.) is 1/1000 gramme or 0·0154 grain.

Temperature in degrees of the Centigrade scale $C^\circ = \frac{5}{9}(F^\circ - 32)$;

of the Fahrenheit scale $F^\circ = \frac{9}{5}C^\circ + 32$.

Temperature absolute may be taken as the temperature on the Centigrade scale with 273 added, or as the temperature on the Fahrenheit scale with 460 added.

B.Th.U. is the symbol for British thermal unit, the quantity of heat which raises 1 lb. of water 1° F.

1 Therm (the unit of heat for sale of gas) is 100,000 British thermal units.

B.T.U. is the symbol for a Board of Trade unit for the sale of electricity; it is a kilowatt hour.

Weight of a cubic metre of dry air at 0° C. and 760 mm. mercury is 1293 grammes.

G.M.T. means Greenwich Mean Time. Add one hour to get Summer Time

The symbol $>$ is used as an abbreviation for "greater than."

THE SMOKE PROBLEM OF GREAT CITIES

CHAPTER I

THE PROBLEM—HISTORICAL AND GEOGRAPHICAL

The tendency during modern times for people to collect together in great communities or cities has forced the problem of the pollution of the air by smoke on public attention. The concentrated impurity in the air of some of our modern cities is so great that it has become a menace to public health as well as a serious source of financial loss to the community.

While this concentration of people into cities has caused a great aggravation of the smoke problem in such places, its cause can also be traced to the immense growth of populations, with the consequent increase in the quantity of coal consumed, and, therefore, in the amount of smoke.

The smoke nuisance is, in itself, no new thing, but has existed ever since the introduction of bituminous coal as a fuel.[1]

Prior to the discovery of coal the fuels in common use were wood and charcoal, the former producing little smoke, while the latter is entirely smokeless.

In the British Isles the immense deposits of bituminous coal which are available have naturally led to the use of this fuel in great quantity. Had these deposits consisted of anthracite, for example, we should have had no smoke problem to deal with. Thus we find that the geological

[1] For details of the history, the reader may be referred to "A History of Coal Mining in Great Britain" by Robert L. Galloway. (Macmillan & Co., London, 1882.)

formation of a country may be indirectly responsible for the existence of a smoke problem.

The word "coal" is often found in the Bible, but it cannot be regarded as referring to our modern product, but almost certainly to charcoal. For example, King Solomon, in Proverbs xxvi. 21, says: "As coals are to burning coals, and wood to fire; so is a contentious man to kindle strife." There is a possibility that he referred to bituminous coal, since his empire contained Syria, a country containing coal and bituminous pits. There is thus the possibility that he was acquainted with the use of bituminous coal as long ago as 1016 B.C., or about 3,000 years ago. Again, we find in the book of Isaiah (xlvii. 14) the statement that "there shall not be a coal to warm at," and in Lamentations iv. 8, written probably about 650 B.C.: "Their visage is blacker than a coal."

In somewhat later times, that is, about 300 or 400 B.C., or 2,000 years ago, we find the Greek orator Theophrastus, a friend of Aristotle, writing: "Those substances which are called coals and are broken for use are earthy, but they kindle and burn like wooden coals." This can only refer to coal as we now know it.

Tools and cinders found in England near the old Roman wall show that before 54 B.C., when the Romans invaded England, the Britons were acquainted with the use of coal. Referring to the same Roman wall, the Rev. A. H. Sayce writes: [1] "From Chesters we went to Housesteads, the ancient Borcovicus, and there inspected the prefect's coal cellar, where pieces of coal were still lying in the recently excavated soil."

The first actual record of the use of coal in England is a receipt given by the Abbey of Peterborough in A.D. 852 for "twelve cartloads of coal." We find records of mining operations in A.D. 1180, in the books of the Bishop of Durham, and there is no earlier record.

There is a curious reference to a stone called gagates (jet) in the writings of the Venerable Bede, who flourished at Jarrow-on-Tyne early in the eighth century. He does not

[1] "Reminiscences," p. 270.

say it was used for fuel in the ordinary way, but that, when kindled, it had the property of driving off serpents. It is, however, clear that until about the end of the twelfth century wood, charcoal, and peat were the fuels in general use.

In the early Norman era chimneys were rare ; it was only in the massive walls of castles or other buildings of substantial character that such luxuries as chimneys could be constructed. The walls of the houses of the common people were of wood ; the fireplace was a hollow in the middle of the floor, which could be covered when the fire was not required, and all fires had to be extinguished at a certain hour of the evening on the ringing of the curfew. The smoke made its escape as best it could, either through a hole in the roof or through the doorway. It is clear that bituminous coal could not have been used to any extent under such circumstances.

It appears that the first coal to be mined in England was dug out from the sea shore when the carboniferous strata were exposed by the washing of the waves and tides, and this is probably the reason why such coal was known for a long time as sea coal to distinguish it from charcoal. Thus we find that on the south shore of the Firth of Forth coal was being raised as early as 1214, as one of the grants made by William the Lion to the monks of Holyrood Abbey, Edinburgh, was the tithe of the colliery of Carriden, near Blackness. We also find that in 1228 a lane in a suburb of London was known as "Sacoles Lane" (Sea Coles Lane), showing that there was at that time some trade in sea coal. When once the working of coal had been commenced, its use spread rapidly, and before the close of the reign of Edward I. in A.D. 1307 it was being dug to some extent in most of the coalfields of England, Wales, and Scotland.

As soon as the use of coal became at all general the smoke nuisance made itself felt, for it is recorded in the annals of Dunstable that in the year 1257 Eleanor, Queen of Henry III., was obliged to leave the town of Nottingham, where she had been sent to stay during the King's absence in Wales, and removed to Tutbury Castle instead, owing to the smoke of the sea coals.

In London it is recorded that in the year 1273 sea coal was prohibited from being used as being "prejudicial to human health," and even the smiths were obliged to burn wood. Towards the end of the reign of Edward I. the use of coal in London had increased to a great extent. In spite of efforts to check its use, brewers, dyers and others who used much fuel had commenced to burn coal instead of wood and charcoal; the nobles, prelates and others going to London to attend Parliament were greatly annoyed by the increasing smoke, and took the lead in getting up demonstrations against the obnoxious fuel; they were joined by a great body of the populace. In consequence of the agitation, a Royal proclamation was issued in 1306 prohibiting artificers from using sea coal in their furnaces. Little notice seems to have been taken of this prohibition, and complaints still continued, so that it was decided to have recourse to stronger measures in order to put an end to the use of coal. In 1307 a Commission of Oyer and Terminer was appointed with instructions—

"to inquire of all such who burnt sea coal in the city, or parts adjoining, and to punish them for the first offence with great fines and ransoms, and upon the second offence to demolish their furnaces."

It is recorded that one man who disobeyed the King's command was tried, condemned to death, and executed for burning sea coal in London.

It is at least clear that the smoke nuisance was felt strongly as long ago as 1257. The first record of a smoke abatement association is that referred to above as having been formed by the nobles in 1306. Up to this date we find no records of the use of coal as a domestic fuel, but its advantages very soon caused it to displace partially or wholly the wood and charcoal then in use, and in 1313 the monks of Jarrow monastery used coal for domestic fires. A mixture of coal and wood was widely used in localities where coal was plentiful.

The use of stones for fuel was regarded by those unacquainted with coal as strange even in later years. Æneas Sylvius (afterwards Pope Pius II.), who visited Scotland

about the middle of the fifteenth century as papal legate, says in his commentaries that he saw poor people who begged for alms at the churches going away quite pleased with stones given to them as alms, and he adds: "This kind of stone, being impregnated with sulphur or some fatty matter, is burnt instead of wood, of which the country is destitute."

Towards the end of the sixteenth century the scarcity of wood had caused the people to use coal to a very great extent, and the same scarcity caused coal to be used again by the London brewers, as is shown by a petition presented to the Council in 1578 by the Company of Brewers offering to use wood only in the breweries near Westminster Palace, as they understood that the Queen "findeth hersealfe greately greved and anoyed with the taste and smoke of the sea-cooles."

Howes, writing in 1631, says that "within thirty years last the nice dames of London would not come into any house or room where sea coals were burned, nor willingly eat of the meat that was either sod or roasted with sea coal fire."

A very quaint pamphlet was written in 1661 by John Evelyn, entitled "Fumifugium," in which he says:—

"The now Duchesse of Orleans who at her Highnesse late being in this city (London) did in my hearing complain of the Effects of this Smoake both in her Breast and Lungs." He suggests as a remedy: "The culture and production of such things, as upon every gentle emission through the aer, should so perfume the adjacent places with their breath; as if, by a certain charm or innocent Magick, they were transferred to that part of Arabia, which is therefore styled the Happy." He goes on to say: "I have presumed to offer these few proposals for the Meliorating and refining the Aer of London; being extremely amaz'd, that where there is so great an affluence of all things which may render the people of the vast city, the most happy upon Earth; the sordid and accursed Avarice of some few Particular Persons, should be suffered to prejudice the health and felicity of so many. . . . That men whose very Being is Aer, should not breathe it freely when they may; but (as that Tyrant us'd his vassals) condemn themselves to this misery and Fumo præfocari, is strange stupidity; yet thus we see them walk and converse in London, pursued and haunted by that infernal Smoak. . . . That this Glorious and Antient City . . . should wrap her stately head

in Clouds of Smoake and Sulphur, so full of Stink and Darkness. I deplore with Just Indignation." Referring again to London smoke, he calls it " That Hellish and dismall clowd of sea-coal which is not only perpetually imminent over her head . . . but so universally mixed with the otherwise wholesome and excellent Aer, that her Inhabitants breath nothing but an impure and thick Mist accompanied with a fuliginous and filthy vapour, which render them obnoxious to a thousand inconveniences, corrupting the Lungs, and disordering the entire habits of the Bodies: so that Catharrs, Phthisicks, coughs and consumptions rage more in this city than in the whole Earth besides."

Coming now to later years, we have an Act passed in 1853 to abate the smoke nuisance from shafts and steamers above London Bridge. In 1858 another Act came into operation, applying to steamers below London Bridge and to potteries and glasshouses, previously exempted. Still later we have the Public Health Act of 1875, which contains the statutory law as to smoke emission throughout England, except in London and a few provincial cities having local Acts. In London smoke emission is dealt with by the Public Health Act (London), 1891.

Thus we see that throughout practically the whole history of coal as a fuel the smoke given off has been a source of continual trouble.

CHAPTER II

THE NATURAL VENTILATION OF GREAT CITIES, AND ITS FAILURES

Fluctuations in Smokiness

The problem that confronts us at the outset of an inquiry into the pollution of our atmosphere is the alternate success and failure of the natural processes of scavenging. Relying upon trustworthy observations, of which particulars will be given in a later chapter, we may express the range of the irregularity in the state of the atmosphere as regards pollution by saying that on a clear day a cubic centimetre, 1 c.c. (Fig. 1), a small thimbleful, of the air which we have to breathe will contain as many solid particles as there are words on a page of this book; but on a smoky day there may be in the same volume as many black particles as the whole number of words in the book. The difference between those conditions, vast as it is, is not to be accounted for by any extraordinary ebullition of smoke on the smoky day, such as may indeed happen locally if a neighbour's chimney gets on fire. The differences occur when the output of smoke cannot be said to have varied. The real cause is the failure on occasion of the natural scavenging of the air, which is generally so admirable that the majority of city folk have not got out of the habit of leaving everything to its care. Those occasions are reminders of our part in the responsibility for the condition of our own atmosphere, reminders which are soon forgotten, but always recur. The winters of 1923–24 and 1924–25 were specially prolific in reminders. Notably foggy days of two sorts were recorded. Surface fog, so thick that traffic was generally suspended, occurred on November

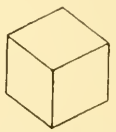

Fig. 1. — A cubic centimetre, natural size.

24th to 27th, 1923, December 10th to 12th, and 21st, 1924, and again in 1925 on January 10th to 12th. The other kind, high fog which gives the darkness of midnight in the daytime, was noted on January 23rd, 1924, repeating an experience of the same date in 1912, and on November 11th and December 2nd, 1924.

Wind is the natural scavenger of our atmosphere ; we can realise that fact by the way in which a thick winter fog is cleared away as soon as even a light wind begins to blow. A wind which registers six miles an hour on an anemometer in an exposed situation outside London is quite sufficient to sweep away any ordinary fog. That is not by any means the case on mountains or at sea, where fogs can occur even with strong winds ; but the conditions which produce fogs on mountains and at sea cannot easily occur in a town.

According to the records of wind at the Royal Observatory, Greenwich, the mean movement of the air over London is between eleven and twelve miles an hour, or 280 miles in the twenty-four hours. That is sufficient to keep the atmosphere moderately clean, but on some days the drift of the wind is only fifty to ninety miles in the day, and then the scavenging of the London atmosphere fails.

The effect of wind in clearing away the fog or haze that is composed mainly, if not entirely, of smoke, can be demonstrated in other ways than by personal experience. Dr. Owens has plotted the relation between the wind-speed as registered by an anemometer at Kew Observatory, in the Old Deer Park at Richmond, and the amount of smoke at the same time in the air of Westminster. The inverse relation between the two is very striking. Taking all the observations together, it is clear that, as the velocity of the wind goes up, the amount of smoke in the atmosphere goes down. A note on this investigation will be appended to this chapter.

The Dispersal of the Particles of Soot by Eddies

The lessons to be drawn from the chimney on fire deserve a few moments' consideration. It is generally by the smell of burning soot that we first become aware of it, wherever

we may happen to be, out of doors or indoors. The smoke of burning soot is peculiar in respect of its pungent smell. It is not on account of the heaviness of its particles that it finds its way so surely to the street or indoors. It is only a striking example of the mechanical process of the mixing of any particular portion of air with its surroundings which is always going on in the atmosphere, particularly near the surface, in consequence of the irregular motion always present and included in the comprehensive term *eddy*, or the more general term *turbulence*. When we fully understand all that lies concealed in, or is at least covered by, those words, our knowledge of the atmosphere will be complete. At present we are a long way off that consummation ; but already we have learned a good deal about eddy motion. Ordinary smoke mixes with the air of its neighbourhood in consequence of the natural eddies, just as that of a chimney on fire does, but there is less of it coming from any one spot, and the smell of it is so familiar that on ordinary days it causes no surprise. On some days one can see the smoke pouring from ordinary chimneys down into the streets ; the spurt that corresponds with afternoon tea is generally the most favourable opportunity for watching it. But whether we notice it at the time or not, the eddies and the mixing are always going on, and, by the natural processes of the atmosphere, the smoke of all our chimneys is spread with astonishing equality—" fairly equally " is the cant phrase of the sciences, " unfairly equally " a student of atmospheric pollution would say—over a thick layer of air from the ground upwards.

The Stratification of the Atmosphere—Ceilings or Decks.—Yet the layer that carries the smoke is not always of the same thickness ; far from it. That brings us to the second important feature of the structure of the atmosphere, the separation into layers. The layering or stratification is brought about by temperature. We are accustomed to think of the atmosphere from the point of view of our experience within doors. Everybody knows that the warmed air of rooms is to be found at the ceiling or on the way there, and out of doors, where there is no ceiling to be seen, well—

warm air rises, and nothing more need be said about it. There is, however, a limit to the ascent of warmed air in the open, even on the calmest day, and, indeed, the limit is generally most restricted on the calmest days for a reason that will become apparent.

The limit is set by the fact that the pressure of the air diminishes with elevation—inevitably so, because the pressure at any level is simply made up of the weight of the atmosphere above it, and as we leave part of the atmosphere beneath us when we climb, there is naturally less above us, and therefore less pressure. So air as it rises is subject to the reduction of pressure which happens to represent the state of the atmosphere at the time ; and, with air or any other gas, reduction of pressure produces automatically a reduction of temperature. So familiar is the relation between compression and temperature change that we are accustomed to refer to it as the " bicycle pump " action. So long as the air is dry the changes are perfectly reciprocal ; compression causes increase of temperature, rarefaction decrease. It is rarefaction that we are thinking about with rising air and consequent cooling. We know also the amount of the cooling, provided that the air under operation is protected from gain or loss of heat in other ways, as by conduction or radiation. So long as the air is dry it is expressed by a well-known law,[1] and it works out in practice at the easy rule of one centigrade degree loss for 100 metres elevation, 1° F. for 172 feet. Meteorologically speaking, the air is " dry " so long as it is not " saturated " with moisture. If saturated air rises, cloud is formed automatically, and the thermal consequences are rather complicated. For elevations not very far from the ground the ordinary loss of temperature of saturated air in our latitudes is about half a degree centigrade for 100 metres, or about 1° F. for 300 feet. We shall not have to deal in any sort of detail

[1] The algebraical formula is—

$$\log \frac{t_1}{t_0} = 0{\cdot}29 \log \frac{p_1}{p_0}$$

where t_0, t_1 are the initial and final temperatures measured from 273° C. below the freezing point of water, p_1, p_0 the corresponding pressures. The condition of protection from gain or loss of heat is expressed by saying that the change is *adiabatic*.

with the formation of cloud in this way, so we may confine our attention to dry air, which loses, as we have seen, very approximately, 1 degree of temperature for every 100 metres of elevation. The fall of temperature in the surrounding atmosphere through which the warmed air has to rise is not generally so rapid as 1 degree for 100 metres. It would be so if the air in the layers under consideration could be completely mixed by some effective process of mechanical stirring which would bring the air into a condition which is described as "convective equilibrium for dry air." It is so on some occasions, and then the warmed air goes through it without stopping, as it does in a closed room, till it gets to a "ceiling." It will find a natural ceiling as soon as it reaches a layer in which the rate of fall of temperature is less than one degree per 100 metres, and the ceiling will be more effective the further the actual condition departs from that ideal.

Investigations of the upper air within the last twenty-five years have disclosed the permanent existence of a very efficient ceiling at the lower boundary of an upper layer of the atmosphere, about six miles above the surface, which is called the stratosphere, in which there is no change of temperature with elevation, as distinguished from the lower layer or troposphere, between the stratosphere and the surface. In the troposphere there is a fall of temperature with height of very variable amount, because it ranges in different places and at different times between the limiting value of 1 degree for 100 metres and what is called an "inversion," in which temperature increases with height instead of diminishing, and in which, indeed, the increase of temperature, especially near the ground, is sometimes very great, 15 to 20 degrees within 1,000 feet.

An inversion of that kind is a complete stopper or ceiling, or lid, or deck, for rising air. As we have seen, the air, in rising, loses automatically a degree in every 100 metres; if there is a rise of temperature of 5 degrees per 100 metres in the environment, an initial excess of temperature of 6 degrees—a very large one—would be disposed of in 100 metres; 1 degree would be lost by its own behaviour, and

the remaining 5 degrees of difference through the change in its environment. We call 6 degrees a very large temperature difference, because, in the free air, what is being warmed does not wait till so large a difference has been established ; it moves off as soon as warming begins. And when quite hot air is delivered through a chimney, it soon mixes with its environment and the excess of temperature becomes very much diluted, as one may see by the way in which smoke from a chimney behaves in a wind.

These lids or "decks," represented by inversion layers, that is to say, by layers in which temperature increases with height, are of the greatest importance in relation to the behaviour of smoke on different days. On an ordinary day the loss of temperature with elevation in the environing atmosphere may be as much as five-tenths of a degree for 100 metres, so that a sample of dry air with 1 degree of superiority of temperature, and cooling at the rate of 1 degree for 100 metres, will have to go up 200 metres to find its equilibrium, whereas, if it begins to rise in an inversion with the atmosphere warmer by 5 degrees for 100 metres, equilibrium will be gained in less than twenty metres.

Decks of the kind here described may be identified not only as lying on the ground, but at various levels in the free atmosphere. Layers of cloud of the type called stratus or strato cumulus, which consist of a continuous sheet or of more or less regular rolls or waves, and indeed from their appearance suggest a ceiling, are generally surmounted by an inversion or deck. But an inversion can exist without any cloud beneath it, and is none the less real on that account ; it forms a very effective stratification. The thickness or difference of level between its upper surface and under surface may be as much as a kilometre, half a mile, or more. A balloon ascending very slowly from below will rebound from its under surface, and one descending slowly from above will similarly rebound from the upper surface like a fishing float in water. What happens is that the balloon, just too heavy to be supported, drops into a layer which is colder, and therefore denser and more buoyant, so the balloon is forced up again. The buoyancy is only

temporary, because, when the balloon settles down once more into the cold environment, its own gas gets cooled in time, and it can pursue its downward journey after a temporary delay in passing through the deck, which is represented by the inversion.

"Decks" Lying on the Ground

One of the most frequent and most obvious ways of Nature for building lids or decks on the ground is a clear sky in a calm night. The ground cools of its own accord—by radiation to the clear sky we say; that is our name for the process, which is very conspicuous—in the formation of dew and hoar frost. The cold ground itself cools the air above it, and the air, cooled in the calm, flows down hillsides like water and collects as pools and streams of cold air in the valleys. Perhaps the moisture in the air itself helps to continue the cooling by radiation from the water vapour, for water vapour is not transparent to heat as dry air is; or perhaps the slow eddy motion churns up the air of the surface layers enough to cool the mixture below its dew point. By this simple process a perfect atmospheric lid or deck is laid on the ground, perhaps 400 feet thick in the London basin, and the smoke of our chimneys is just as securely trapped and confined as by a solid ceiling. The effect which layers of successively higher temperature have in forming a lid or "deck" which is impermeable even to warmed air has been likened to the reinforcement of concrete by steel rods. The more rapid the increase of temperature with height, the stronger, or less deformable, is the layer. It is, of course, to be understood that it is only against air or other gases of like density that the inversion is an impenetrable barrier: rain and snow, shells, aerial torpedoes or other missiles would draw no distinction between it and any other air, but against its own kind it is adamant, even when its own kind carries all the water that it can.

Consequently, whenever in the London area we get a cold surface layer with air getting warmer higher up, as we do on clear nights at any time of the year, the scavenging fails

entirely. There is no chance for the smoke to reach the levels of 500 metres or more, where the wind very seldom fails; it is all kept down easily within the level of a little more than the top of St. Paul's, and we get a concentrated mixture of air and smoke. The mixture is the more concentrated the steeper the increase of temperature with height, that is to say, the colder the surface; and, sad to relate, the surface is colder the clearer the sky.

The Relation of Fogs to "Decks"

We have said nothing yet about the formation of fog; we have considered simply the failure of the scavenging of the smoke; but, at the same time, the conditions for the failure are the conditions for the formation of fog in town or country. The process of cooling, partly by radiation from the air itself and partly by radiation from the ground, where the air is subject to the churning of the eddies due to slow drift or settlement into the valleys, gives a body of air close to the ground, often extending only a little way up, which is cooled below its own dew point. If there are hygroscopic nuclei, such as may be found in abundance in town air and in quite considerable numbers in country air, it is not necessary to reach the dew point, though we are unable to say exactly how near an approach to it is demanded by Nature before she allows a cloud of water drops to form.

Thus the conditions for intolerably smoky air and for an ordinary water fog are practically identical, and the history of the process is instructive. The first sign is a calm area over the neighbourhood, as shown by the lack of pressure-difference in a weather map, then a clear sky and approaching night, which results in a cooling surface and the formation of an atmospheric deck. Fog begins to form, generally in the parks and open spaces first, and the cloud spreads itself through the city. Such smoke as there is is confined to the layers within the deck, and the more reinforced the deck the more concentrated the smoke; smoke is nearly always noticeable indoors when the streets have fog. In the morning there is a white fog, not distinguishable from a country fog;

by eight o'clock it has to take on the new day's load of smoke, and by nine o'clock it is dirty. In the course of the morning, if we had the waste heat of the chimneys without their smoke, we might score a few points over the country by using the aggregated warmth of our dwellings to compensate the loss of heat to the clear sky. That indeed is quite likely, for London is always "a coat warmer" than the country, and to dissolve a fog by the superfluous warmth of our buildings would be a considerable triumph of civilisation, which has hitherto failed to modify climate; but the triumph is marred by the replacement of the water particles of a country fog by the smoke particles of a town fog, which are very disagreeable to the eyes, the nose, and the mouth. Yet in their turn they are just as effective, when night comes, in losing heat by radiation to the still clear sky above them as the ground itself, whence it follows that, as day by day goes on, each supplies itself with a morning wet fog of the type familiar to us in the country. It will probably be changed in the middle of the winter day, not for the bright sunshine of a country day, but for the smoke fog of a great city, and at nightfall it will be converted into that combination of water drops and smoke which is the despair of the cleanly housewife.

Fog and Haze

From what precedes it will be noticed that we have two separate kinds of thickness of the atmosphere, one of which consists of water drops due to the ordinary meteorological process of condensation of water vapour upon nuclei of unknown composition, which produces a white cloud; this can only be produced when the temperature of the air is at least very near the normal dew point. The other consists of particles of soot or smoke, and is not necessarily related to any particular degree of humidity of the atmosphere.

Though in practical experience they shade into one another, we propose to draw a distinction between these two conditions, as physically they are not necessarily related, except from the fact that the same meteorological conditions

are suitable for either. We propose to restrict the name *fog* to a cloud of water globules, whether fouled by smoke or not, and to use the word *haze* for a cloud, which is not necessarily dependent upon water globules.

The Suspension of "Particles" in Air

Soot particles, which are the chief constituent of the smoke of towns, are heavier than air, and if the air were quite still, they would gradually settle out of it. They are retained in the atmosphere by the eddy motion or turbulence which is always operative whenever the air is moving, although the motion may indeed be very slow. In still air even small particles would find their way to the ground, but particles of the ordinary size of those which have been found in smoke would take about three weeks to travel downwards through 100 feet; and in moving air their chance of settling is so small as not to count. These are particles about one-half of a micron in diameter. The larger particles, such as the "blacks" which are formed by the coagulation of soot in chimneys, or the dust which is carried into the air by strong wind, fall much more rapidly and "settle" on exposed surfaces with facility.

The processes of stirring and settling act in course of time as a screen or sieve for smoke, which contains particles of different sizes. The larger particles settle; the smaller ones are prevented from settling by the motion of the air, and in course of time the particles retained show a surprising uniformity which is not disclosed in the smoke which is examined soon after being formed. The process is somewhat similar to the screening action of sea waves, which produce a deposit of sand on the foreshore which is made up of particles of surprising uniformity.

The amount of impurity which is contained in the atmosphere of London in the smokiest part of an ordinary winter day amounts to about a milligramme in a cubic metre, or about one-millionth part of the weight of the air which carries it. A heavy smoke haze may contain 5 or 6 milligrammes of soot per cubic metre, or even as much as ten

times the amount carried in a lighter haze, and more than a hundred times as much as that in the same volume of air on a clear day.

Water Particles

Particles of soot are not the only load which the air may carry on foggy days: there are also the particles of water which form the water fog. The amount of water carried in this way may be as great as 5 grammes per cubic metre, a thousand times the weight of the soot in a thick smoke haze. The water particles are much greater in size, ranging from 5 to 20 microns in diameter, whereas the particles of a steady smoke fog are of the order of half a micron.

The difference in size of water particles and smoke particles, to which attention has been directed, is probably responsible for a striking phenomenon which is often observed in the case of town fog as distinguished from country fog, and that is the redness of the sun when its disc is just visible through a town fog in comparison with its whiteness when seen through a country fog or a fog at sea, or through one of the thin high clouds which sometimes veil the sun without obliterating its form. This notable difference is due to what is known as the selective scattering of light by very small particles. Scattering is the process by which we see the shapes of translucent bodies like clouds, as well as the faint blue haze of distant hills or the blue of the sky. The comparatively large globules of an ordinary water cloud or water fog scatter all the light equally, irrespective of colour; but when the particles are so small that their size becomes comparable with the length of the waves that constitute light they fail to scatter the red light, which has long wave-length, but continue to scatter the blue light, which has shorter wave-length, and the difference in the effect upon the two is very marked. Hence a cloud of coarse particles looks white in sunlight, and white also by transmitted light, when it is not so thick as to stop all transmission; but a cloud of very fine particles in sunlight looks blue when the observer can see only the scattered light, that is, when he looks down the sun's rays or across them; but it looks red

when the sun is viewed through the cloud. Smoke clouds are fine enough to cause this selective scattering, and water clouds are not. In this way we may explain a very notable phenomenon, that a water fog may be so thick as to prevent one seeing any trees at all unless they happen to be between the observer and the sun, and then the twigs stand out clearly defined on the sun's disc, which is red if the fog contains a considerable number of fine smoke particles.

We are entitled to conclude from an observation of this kind that the smoke particles are acting upon the light independently of the water particles. The water particles, in the sunshine, scatter a considerable fraction of the light, irrespective of colour, and the illuminated white cloud prevents our seeing the tree at all if there is no bright background; but with the bright background of the sun there is light enough transmitted to enable us to see the twigs, but it is coloured red in transmission by the fine smoke particles. We cannot suppose that any water is condensed on these particles, for if there were, they would be too big to produce any reddening; the water globules are condensed upon another set of particles.

Hygroscopic Nuclei

Besides smoke particles in an atmosphere free from water fog, we must allow the existence of nuclei upon which the particles of fog can form, because it was proved many years ago by John Aitken that without nuclei globules of water cannot condense from the atmosphere. We call these nuclei hygroscopic nuclei. In dry air they are even smaller than the black smoke particles, though they may be formed in abundance in smoke that comes from fuel which contains sulphur. Others of a different composition may come from the evaporation of the spray of sea water. These nuclei are so minute that they cannot be identified directly; they only come into notice when water is condensed upon them. But they may possibly come to the aid of the smoke particles in producing the red colour of the sun at sunset, when the path of the sun's rays through the atmosphere is very long.

They can hardly be regarded as operative when the sun appears red at some considerable height above the horizon, because the path through the atmosphere is so short. The colour is then probably caused by smoke alone. The beam passing through a fog is barely a kilometre or half a mile in length, whereas the atmospheric path of the rays from the setting sun is several hundred times that length, and as the blue of the sky is formed by the scattering of the sunlight, the residual light which is transmitted must have a reddish colour if the path is long enough.

The hygroscopic nuclei are probably minutest particles of the oxides of sulphur, derived from sulphur dioxide, the original product of combustion, which in sunlight changes rapidly into sulphur trioxide or sulphuric acid. Particles of sea salt made up of chlorides of sodium or magnesium would be similarly effective.

Examples

1. 1923. November 24–27.—A good example of the banking up of the smoke impurities over a city when the meteorological conditions are suitable was provided during the days from November 24th to 27th, 1923, in London. The city, during the days mentioned, was under a thick smoke haze for most of the time. The weather was abnormally cold, with frost at night. The wind, which on the 24th was very light from the north or north-west, gradually failed, and on the 25th, 26th and 27th it was very light and indefinite. According to the Monthly Weather Report published by the Meteorological Office, "On the 25th a dense and unbroken fog prevailed over the south of England, stopping all shipping movements in the Thames and Southampton Water, and preventing the landing of aeroplanes from the Continent." It is practically certain that during this time there was an "inversion" of the vertical temperature gradient, which is a condition normally accompanying fog.

Thus we had a failure of the wind to carry away the impurities, and a failure of the upward currents due to the

warm air from the chimneys to penetrate the surface layer, because the lapse rate or temperature gradient had become inverted. The result of this was not only that the smoke produced in the city was not carried away laterally by the wind, but it was also collected into a comparatively thin

Fig. 2.—Density of smoke in the air of Westminster, November 24th–27th, 1923.

layer near the ground. The density of the smoke haze in London showed a regular oscillation each day between the 24th and the 27th. The greatest density occurred about midday, after which it gradually diminished to a minimum until the growth of the following day's smoke caused the density to rise again, starting about six o'clock in the morning. The accompanying diagram (Fig. 2) shows

graphically the way in which this particular smoke haze varied. It is prepared from records taken in Westminster by the automatic recording instrument, which will be described in a subsequent chapter. It shows the density of the haze in milligrammes per cubic metre.

It will be seen that in the instance recounted above the two varieties, that is, smoke haze and water fog, co-existed, thus illustrating the fact that the conditions which favour the formation of fogs are also appropriate for the formation of smoke haze, when there is a sufficient supply of smoke for the purpose. Another factor which tends to aggravate matters is that, since during foggy weather it is often very cold, this causes people to burn more coal for heating their houses, and so the amount of smoke is increased at the very time when the scavenging arrangements of Nature have failed.

It is probable that in the November fogs referred to, and others of a similar nature, the condensed water particles are partly evaporated in the warmer air over great cities, but replaced by smoke particles. It is not uncommon, for example, when coming up to London from the country during foggy weather, to find the limit of visibility somewhat greater in London than in the surrounding country, while at the same time enormous numbers of small smoke particles can be detected in the London air which are absent, or, at any rate, much fewer in numbers, in the country. This suggests that the quantity of condensed water in the London air must have been reduced, since the limit of visibility was increased in spite of the fact that large numbers of smoke particles were added.

Instead, therefore, of taking the usually accepted view that a London fog consists of condensed water particles dirtied by smoke and oily hydrocarbons, it appears probable that it consists of a combination of smoke haze and water fog, in which the latter has been replaced to a variable extent by the former.

2. 1924. December 10–11.—A heavy fog overspread the greater part of the south of England on December 10th and 11th, 1924, and during its prevalence observations were

made from a kite balloon flown at the Croydon aerodrome,[1] the chief purpose being the collection of reliable data as to the visibility of lights, and generally the investigation of means for bringing aeroplanes into the aerodrome during fog. The observers found during the first night's fog that, on reaching about 300 feet above ground level, they came out into brilliant moonlight, all below being an unbroken sea of swirling mist. Next morning, Wednesday, December 10th, the balloon went up again, and the fog was found to be again about 300 feet thick; above this was brilliant sunshine, while during later observations the fog belt extended to between 500 and 900 feet above the ground. Observations were made at the same time at Kew Observatory by means of a captive balloon;[2] a very well-marked inversion of the lapse rate of temperature was found. On December 10th the temperature from the ground to about 300 feet was approximately 34° F. At about this level an increase was noted and continued until, at about 400 feet, the thermometer had risen to over 45° F. Beyond this level it remained nearly constant at a little over 45° F. up to 1,250 feet. On December 11th a similar inversion was again found, but at a higher level. From the ground to a level of about 700 feet the temperature was just over 30° F.; then commenced a rapid rise, so that at a level of about 800 feet it was just under 45° F., and remained about that figure to beyond 1,250 feet. Of course, the fog referred to here was an ordinary condensation fog, but the conditions are described since it is a well-marked example of inversion of the lapse rate or vertical temperature gradient, which has been referred to already.

High Fogs and the Gloom of Cities

Another type of weather in which Nature's arrangement for the scavenging of the air of great cities fails is that of the days of darkness when, in the middle hours of the day, it

[1] Biddlecombe: *Meteorological Magazine*, No. 708, January, 1925. H.M. Stationery Office.

[2] F. J. W. Whipple: *Meteorological Magazine*, No. 708, January, 1925. H.M. Stationery Office.

becomes as dark as it is usually at midnight, and, indeed, the day becomes little different from the depth of night. In that case, apparently, we have not the exceptionally impenetrable lid which keeps the products of combustion of our coal within a layer less than 400 feet thick, counting from the ground, though there is probably an inversion over a cloud some 2,000 feet up. By the absence of inversion nearer the ground, we are privileged to use for our smoke a thickness of atmosphere extending to 2,000 or 3,000 feet, and in consequence our modicum of particles of dirt does not reach a very high figure ; traffic is ordinarily possible, though artificial light is required. What has failed in this case is an air current in the higher levels, almost invariably to be found within a height of 4,000 feet, which can carry away our waste products.

Meteorologically the situation is an interesting one. There is a certain type of London weather which, in winter, as indeed also in summer, though the consequences are different, is represented by a flow of air from the East over the Continent facing a similar flow of air from the West over the Atlantic Ocean. In winter the Continental stream is cold, and the Atlantic stream warm. The westerly current turns northward and, flowing over the British Isles, goes towards Spitsbergen. The easterly current divides, one part turning north, and, running side by side with the westerly, gives two adjacent streams with a marked difference of temperature between them, a very frequent cause of fog ; another part turns southward, and between these three currents is a triangular patch without any provision for air motion. Apparently it extends to a considerable height, and within that height our smoke, with some condensed water drops, forms a cloud which is widespread enough and thick enough to prevent the penetration of any daylight to our streets. Contrary to the relatively dry conditions which are usual with the smoke fog due to a cold surface, the darkness belongs to a moist, drizzling type of weather, and we must, therefore, conclude that some considerable amount of condensation is taking place up above, more than is necessary to form a surface fog. The juxtaposition of the

warm and cold currents is perhaps a sufficient explanation of that state of things ; but it is clear that our smoke, instead of joining the one or other of the two currents, stays overhead, perhaps tossed or rolled between the two. We are less well informed in cases like this about the failure of wind at the higher levels than we are about calms at the surface ; and for the present we must be content to think that there is a little enclave at the level of the cloud where, over some considerable area, there is no appreciable pressure difference, and, therefore, there is no wind ; the uniformity extends down to the surface, so that there is an unusually tall column of calm air.

As illustrating this second type of effect produced when the smoke is banked up over the city, the darkness which occurred in London on January 23rd, 1924, may be referred to, and similarly a later occasion, Tuesday, December 2nd, 1924. In these cases the smoke bank was suspended overhead and did not reach downwards to the streets, not, at least, in any great density. We may assume that conditions similar to those described existed over London on either of the two occasions, with the result that there was a complete failure of the smoke produced in the city to escape upwards beyond a certain level, below which it was impounded, there being no wind to carry it away ; so that the sky at 1 p.m. over Westminster was exactly similar to that at midnight on a dark night. At the same time, the amount of smoke impurity contained in the air near the ground in Westminster amounted to about 1 milligramme per cubic metre, while during dense smoke hazes it may be over 6 milligrammes when the haze is at the street level.

On January 23rd there was an anti-cyclone over the country, with light variable winds and a somewhat low temperature. Although no observations of the temperature of the upper air are available for London and the neighbourhood, the records taken at Utrecht, Brussels, and Helder all show a marked inversion of the lapse rate or vertical temperature gradient at about 2,000 feet above sea level. In the case of the high fogs, as in that of surface cloud, deliverance comes when there is sufficient difference of

pressure in our region to maintain an appreciable wind. We return, therefore, to our starting point and consider the relation of atmospheric impurity to wind.

The Effect of Wind

If a chimney is emitting smoke into a wind blowing past at the rate of twenty miles per hour, it is evident that the smoke emitted during one hour will be spread down wind over a strip of country extending for twenty miles. On the other hand, should the wind be blowing at the rate of one mile per hour, the same amount of smoke would be distributed over a strip extending down wind from the chimney for only one mile. Thus the velocity of the wind is one of the factors determining the concentration of smoke which will be found in any particular place.

If the wind is blowing in stream-line motion and free from eddies, which it rarely is, there is little tendency for smoke to spread laterally or vertically. The turbulence of the wind or the state of eddying motion is responsible for lateral and vertical spread.

If we consider a wind in pure stream-line motion, and smoke emitted from a chimney stack into this wind, there would be a natural tendency for the smoke to remain concentrated in a stream of small sectional area. This tendency appears to arise first from the absence of any lateral movement in the wind which would spread the stream. A curious property of eddy formation in the smoke itself contributes also to the result. The process can be watched by looking at the smoke from the funnel of a steamer when it is travelling through nearly calm air, free from the turbulence which is notable even with a light wind and exaggerated by any increase of wind.

The smoke issuing from the chimney stack emerges with a sort of vortical motion; the stream in the centre of the chimney has roughly twice the velocity of that at the sides, where it is impeded by the frictional drag. This results in a whirling motion; a series of vortices are emitted in which the movement is downwards at the outside of the column of smoke and upwards on the side next the

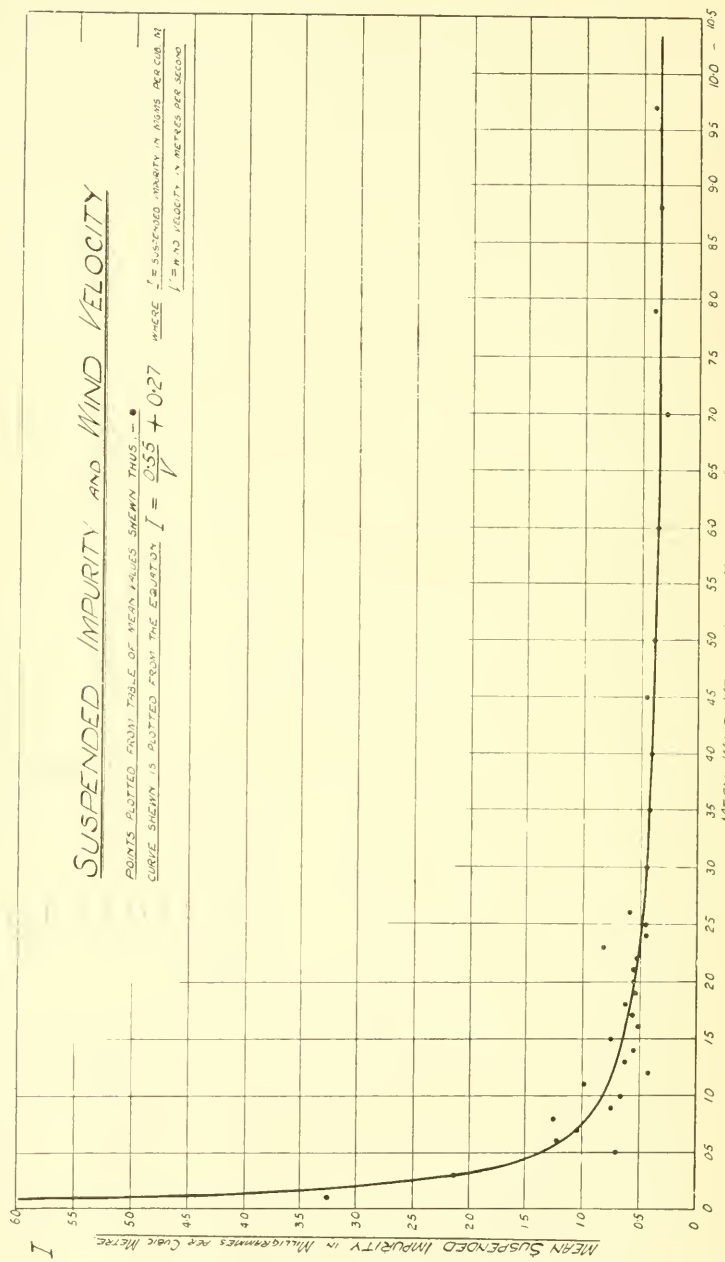
SUSPENDED IMPURITY AND WIND VELOCITY
POINTS PLOTTED FROM TABLE OF MEAN VALUES SHEWN THUS :- •
CURVE SHEWN IS PLOTTED FROM THE EQUATION I = 0·55/V + 0·27
WHERE I = SUSPENDED IMPURITY IN GRAMS PER CUB. M
V = WIND VELOCITY IN METRES PER SECOND
I
MEAN SUSPENDED IMPURITY IN Milligrammes per Cubic Metre
MEAN WIND VELOCITY IN METRES PER SECOND.
0 05 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 - 105

Fig. 3.—Curve showing increased concentration of impurity with failure of Wind.

axis of the column. Thus, considering any diameter across the column, we have an eddy or vortex at each end revolving in opposite directions, which tend to compress the column and keep it compact. Something is therefore needed to break up this system of movement in order to distribute the smoke, and the only source of external energy capable of doing this is the turbulence of wind.

The effect of wind will be illustrated by a curve (Fig. 3) in which the average concentration of impurity at Westminster in milligrammes per cubic metre for each day is plotted against the mean wind velocity at Kew for the same day. The figures are taken from observations of impurity and wind during the period 1921 to 1924. In order to bring out the relation between wind velocity and concentration, the rate of smoke production each day should be about the same. For this reason, the winter figures only were used, when domestic fires were in operation. Further complication is introduced by variation in wind direction ; but as the observing station for impurity was in the middle of the city, the effect may be disregarded, if it may be assumed that the amount of smoke produced is the same on all sides of the point of observation. This is certainly not strictly true, but is probably not so far removed from the truth as to invalidate the method, although it may account for erratic results in individual observations.

The result of the comparison is shown in Fig. 3. The regular increase of impurity with the diminution of the velocity of the wind is quite obvious. It lends itself to representation by an equation which gives the intensity of impurity as having a small residual amount (0·27), even when the wind is beyond any limit likely to occur in practice. From that limit it increases by an amount inversely proportional to the velocity of the wind. The equation representing the relation is

$$I = \frac{0{\cdot}55}{V} + 0{\cdot}27$$

where I is the intensity of impurity in milligrammes per cubic metre and V is the corresponding velocity of the wind

in metres per second. The curve does not give a value for the case of "no wind," and, indeed, the conditions in that case cannot be represented, because they would imply the retention of the smoke *in situ* with continued production, and that state of things cannot be very closely approached.

The expression showing the relation of suspended impurity to wind velocity will, of course, not necessarily be true for other cities or, indeed, other positions in or near London. Its value lies in demonstrating the close relation between the velocity of wind and the intensity of impurity.

The fact that the intensity varies inversely as V is suggestive. It may be due to several different causes. Perhaps, owing to the comparative proximity of the production of the smoke, the vertical spread has not time to develop. Some of the smoke undoubtedly comes from quite near the observation point, and it would probably show little vertical spread. Or we may suggest the possibility of vertical spread being limited in some way; perhaps by an inversion of the lapse rate. Another possibility is that the turbulent layer of wind does not extend to any great height. The turbulence is due to the ground, the eddies being generated at the surface and dying out as the height above ground increases. If this be so, there would evidently be a limit to the upward spreading of dust particles, because they owe their upward spread to the turbulence.

This takes no account of convection currents, which would certainly have an effect; but the great number of observations, extending over four years, tends to diminish their importance, as convection would be only an occasional and not a regular occurrence. Each point plotted represents an average of ten observations, 341 in all.

The Travel of Atmospheric Impurity

When there is a deck or an inversion of the lapse rate of temperature which prevents the smoke from penetrating beyond a very limited height, it will be realised easily that the smoke thus held near the ground is likely to travel to considerable distances across country, provided there is

sufficient wind to drift it along. The concentration in a thin layer prevents the smoke being more widely mixed with the air and thus dissipated, while the slow drift at the same time provides conditions under which impurities may travel over great distances.

The haze which usually accompanies anticyclones, and which is recognisable even in the depths of the country, more especially down wind from any great city, is due to this effect. For example, the authors have observed a dense smoke haze on the south coast of England carried with a gentle northerly wind from the Midlands ; a haze, in fine weather, so thick as almost to amount to a fog at St. David's, in South Wales, during the prevalence of an easterly wind in August ; and persistent gloom at Crinan, in Argyllshire, during the prevalence of a light south-easterly wind in July, accompanied by an indescribable deposit of soot on the calm water.

The travel of atmospheric impurity, taken in connection with the relation between wind velocity and the intensity of impurity, leads on to the consideration of the "dust horizon," the appearance of a horizon, some considerable height above ground level, formed by the upper surface of hazy cloud, such as is often seen from stations at high levels in tropical countries and is noticed occasionally by travellers in aeroplanes in this country. It is, however, not at all exclusively characteristic of the pollution of the air of great cities ; it belongs to the more general question of the residual dust of the lower atmosphere, which opens up too wide a vista for our present purpose.

For further information with regard to the meteorological questions involved in the formation of fog we may refer to the following publications :—

1. "Forecasting Weather." By Sir Napier Shaw, F.R.S., Sc.D. Constable & Co., Ltd., 1923.
2. "London Fog Inquiry, 1901–02." Report to Meteorological Council by Captain Alfred Carpenter, R.N., D.S.O. H.M. Stationery Office, London, 1903.
"London Fog Inquiry, 1901–03." Report of the Council, with Report by R. G. K. Lempfert, M.A. M.O. Publication, No. 160, London, 1904.

3. W. J. Russell, Ph.D., F.R.S.
I. On London Rain.
II. On the Amount of Carbonic Acid in London Air.
III. On the Impurities in London Air.
I. and II. in Appendix to the Monthly Weather Report of the Meteorological Office, London, April, 1884; III. in Appendix to Monthly Weather Report, August, 1885.
4. "The Formation of Fog and Mist." G. I. Taylor, F.R.S. *Q. J. Roy. Met. Soc.*, vol. xliii., 1917, pp. 241–268.
5. "The Report of the Work of S.S. *Scotia* Expedition, 1913." Board of Trade. H.M. Stationery Office, 1914.

CHAPTER III

NATURE AND ORIGIN OF SMOKE

Combustion with and without Smoke

We may define smoke as the mixture of flue gases and suspended particles of solid or liquid matter which is produced by certain fuels during the process of combustion. Strictly speaking, smoke is produced by incomplete combustion ; but our definition will serve to separate smoke properly so called, from grit or dust arising from causes other than the combustion of a fuel.

All fuels have not the property of producing smoke ; it is only a certain number which load the air with solid matter during the process of burning in air or oxygen, or have the power to do so in suitable circumstances. As an example of such a substance we may take the metal magnesium. This is used by photographers to produce the brilliant light which enables them to take flashlight photographs. It is also used in the form of a thin ribbon, which burns with an intense white light and gives off at the same time a smoke composed of magnesium oxide. The oxide produced is white ; it makes itself evident as a white smoke and, if collected, is a very light white powder.

Now if we consider solid carbon and its method of combustion in oxygen, we find that it burns either to carbon monoxide, if the supply of air is deficient, thus :

$$C + O = CO,$$

or to carbon dioxide if enough air is forthcoming ; then

$$C + 2O = CO_2.$$

Both CO and CO_2 are invisible gases ; there is nothing to be seen, no smoke is produced.

In practice we therefore find that charcoal, coke and

anthracite, all of which may be regarded as forms of solid carbon, give off no smoke on burning.

When bituminous coal is placed on an incandescent fire, gases are given off during the first stage of combustion ; it is only when these are completely driven off that we get the incandescent residue of coke. These gases are hydrocarbons, the chief being marsh gas CH_4, ethylene C_2H_4, and acetylene C_2H_2—all composed of carbon and hydrogen. If we burn marsh gas with too little oxygen, solid carbon results thus :

$$\text{Marsh gas } CH_4 + 2O = C + 2H_2O.$$

If enough oxygen is supplied, the carbon is burnt to carbon dioxide (CO_2) thus :

$$CH_4 + 4O = CO_2 + 2H_2O.$$

Here, then, is a type of fuel from which, if it is completely burnt, no solid is set free, and therefore there is no smoke ; while if the fuel is incompletely burnt, solid carbon is set free and smoke is produced ; it is therefore clear that it is from the gases driven off in the early stages of combustion that black sooty smoke arises when we burn bituminous coal.

Coal contains a certain amount of hydrogen, and this burns, as in the above instance of marsh gas, to water H_2O, thus :

$$2H + O = H_2O.$$

Since the water is either in the form of vapour or steam derived from the hydrogen of the coal and from the moisture present in the coal, it cannot be said to form smoke. Again, all coal contains some sulphur, perhaps from 1 to 2 per cent., and this burns to sulphur dioxide (SO_2) :

$$S + O_2 = SO_2.$$

This is also a colourless invisible gas and does not form smoke.

Thus we come to the conclusion that the carbonaceous particles which exist in smoke come entirely from the burning hydrocarbons volatilised from the coal. While these gases are in process of distillation from bituminous coal they are accompanied by yellow smoke, composed of condensed

particles of tar ; such smoke burns with the gases as flame, and, being also composed of hydrocarbons, though in the liquid form, can be very productive of sooty smoke. On the other hand, the yellow smoke may not burn at all if supplied with too little air, or if its temperature falls too low ; in this case it escapes with the flue gases in the unburnt form as tar.

Coal Smoke

Thus we see that there are two main constituents of coal smoke which give it its peculiar property of opacity—soot or carbon from partly burnt hydrocarbon gases or tar, and unburnt tar in the form of condensed vapour ; both of these come from the volatile matter in the coal. There is a close connection between the percentage of volatile matter in a fuel and its smokiness. The lower the percentage of volatile matter, the more nearly smokeless the coal. It would, however, be possible to have two coals containing the same amount of volatile matter, and one of them to be smoky while the other was comparatively smokeless. If, for example, one contains very much more hydrogen than the other, it will tend to make the coal containing it smokeless. There are two reasons for this : first, hydrogen itself does not form smoke ; and second, it has a very high calorific value, as much as 62,100 B.Th.U. per pound. The heat which is produced by the combustion of the hydrogen tends to keep up the temperature of the combustion chamber, and so helps to burn completely the gases evolved.

Soot deposited in flues and chimneys is found to contain a fair proportion of ash ; this cannot come from the hydrocarbons, as they contain none ; it must, therefore, be coal ash drawn up in the draught. It is not very unusual to find, when testing a boiler, that less ash falls through the grate than would be provided by the incombustible part of the fuel. The percentage of ash in the fuel is known from analysis, and considering that some unburnt fuel always falls with the ash from the grate, the residue in the ash pit should be a higher percentage of the fuel than is shown as ash in the

analysis. The percentage is, however, sometimes lower; some of the ash is carried away with the draught.

We may now summarise the ordinary constituents of coal smoke as follows:—

Carbonaceous Matter.—Derived from the incomplete combusion of the volatile part of the coal.

Tar.—Formed in the process of destructive distillation of bituminous coal, and condensed into smoke.

Ash.—Drawn up from the fire by the rush of air passing through the fuel.

Steam.—Formed from the hydrogen and the water in the coal.

Sulphur.—Derived from sulphides in the coal. It exists originally with water vapour in smoke as sulphur dioxide (SO_2), which becomes oxidised into sulphur trioxide (SO_3) and forms sulphuric acid.

Grit.—Particles of unburnt coal or cinder carried away in the draught.

Tobacco smoke, which is formed by destructive distillation of tobacco in pipes, cigarettes or cigars, consists entirely of liquid drops: no flame has been produced, and thus the products of distillation condense into a yellow oily-looking liquid without burning.

The colour of the smoke seen issuing from the chimney top depends upon its composition and the nature or colour of the light by which it is seen. Smoke with a high percentage of tar, say, 20 per cent., appears yellow or whitish, whereas smoke with little tar looks black or brown. It is curious to notice that the smoke from domestic fires is very tarry, whereas that from boiler furnaces contains little or no tar.

The following analysis of soot from domestic and factory chimneys brings out very well the difference between the smoke of domestic fires and that of industrial furnaces:—

Soot from Top of Domestic Chimney

	Per cent.
Carbonaceous matter	55·63
Tar	37·14
Ash	7·23

Soot from Top of Factory Chimney

	Per cent.
Carbonaceous matter	48·21
Tar	0·67
Ash	51·12

If, therefore, a sample of deposited soot be collected in any district and analysed to find the percentage of tar, we can tell with some approximation to the truth what proportion of the soot is from domestic fires and what from boiler and such furnaces. We may for this purpose assume that domestic soot contains 25 per cent. and factory soot 1 per cent. of tar. If we find the sample contains a percentage of tar equal to T, then, calling F the percentage of the sample derived from factory smoke and D the percentage derived from domestic smoke, we may find the relative proportions approximately from the expressions—

$$D = 100\left(\frac{T - 1}{24}\right)$$

$$F = 100 - D$$

Industrial Smoke

We will now consider what are the chief causes of smoke from coal-fired furnaces. Practically we may consider such causes under two heads, as they all operate by bringing about either—

1. A cooling of the gases before combustion is complete ;
   or
2. An insufficient supply of air for the combustion.

Carbon will not burn unless its temperature be about 700° C. or 1,300° F. The gases given off when coal is distilled ignite at a temperature of from 1,100° to 1,250° F. In either case, should the temperature fall below this critical figure, which is called the ignition point, combustion ceases. We will first, therefore, look for the various causes of smoke which operate by cooling below the ignition point.

If the burning gases at a temperature not much above the ignition point strike the comparatively cold plates or tubes of a boiler, they are extinguished ; hence the necessity

of a firebrick lining for combustion chambers when possible, and of sufficient space for the gases to complete their combustion before they become cooled. If an unnecessary volume of cold air be admitted to the furnace the temperature is reduced; every pound of air raised through 1° F. requires 0·24 British Thermal Unit of heat; hence the more air we admit beyond the necessary quantity, the cooler becomes our combustion chamber. The effect of admitting cold air also shows itself after the admission has ceased, as when the door is closed after cleaning fires, the walls of the furnace have been cooled, and they in turn cool the gases given off from the coal, and smoke is produced. Owing to the fact that the flue gases are diluted by the influx of air, the smoke from the chimney top may appear to be reduced when it is really increased in amount. More soot may be discharged in a given time, but thinned out so as to look less dense by the increased volume of flue gas.

Here we see the objection to a method which has been proposed for abating smoke by admitting air through a special opening in the base of the chimney; this does not reduce the amount, but simply dilutes it, and may thus have the practical effect of preventing complaints without actually reducing the nuisance.

Stoking

The addition of fresh coal to a fire always has a cooling effect initially. Before the new fuel has given out any heat by its own combustion, it has first to be warmed to its ignition temperature, about 1,200° or 1,300° F. The specific heat of bituminous coal is about 0·241; hence, if a charge of 50 lb. is fired, $50 \times 0{\cdot}241 \times 1{,}300$ or about 15,665 B.Th.U. will be used in raising it to furnace temperature.

Again, as the gases are distilled off, a large quantity of heat becomes latent in forming the gases from the solid, and all this is taken from the incandescent fuel on the grate.

For these two reasons the first effect of fresh fuel is to cool the furnace, and since it is just during this period of cooling that much of the gases is driven off we often have a state of affairs in which the fall of temperature is so great as to

prevent ignition of the gases. This is very usual with domestic fires. Even if the gases are ignited, the temperature may be too low to complete the combustion. If there is no ignition we have tarry smoke produced, as previously described, and passed out from the chimney unburnt. On the other hand, if the gases ignite we get sooty or carbonaceous smoke produced. The amount of heat abstracted by the fresh fuel is proportionate to the amount of fuel fired, and if a large charge is fired the heat is abstracted very suddenly ; hence the temperature falls lower than if a small charge be fired. The ideal method of firing would be a continuous one in which the fuel is fed at the rate at which it is consumed.

With hand stoking the best we can do is to feed small charges at short intervals. A completely continuous feed can only be attained by mechanical means.

Air Supply

We will now consider insufficient air as a cause of smoke. Practically, the question of air supply is not one of quantity alone ; we have seen that too much may be as bad as too little. The chief points to be attended to in this connection are :—

(*a*) To supply enough, but not too much, air.
(*b*) To supply it at the right place and time.
(*c*) To mix it properly with the gases.
(*d*) If possible to heat the air before supplying it.

Insufficient quantity of air alone is seldom a cause of smoke ; most furnaces receive perhaps one and a half to two times the minimum quantity required for combustion. We have seen that smoke is derived from the volatile matter of the coal ; hence we infer that it is during the distilling and burning of this that attention must be given to the air supply. It is a want of appreciation of this fact which is responsible for much of the smoke produced. A furnace which is receiving its air through the grate only has this supply reduced when a layer of fresh coal is added ; that is, at the moment when the smoke-forming gases are being given

off there is less air than usual being supplied to these gases. It is clear, therefore, that any furnace which does not provide for an increased supply of air during the few minutes after stoking is likely to be a smoky one. To provide for such an increased supply we may have special grids in furnace doors and special air passages through the bridge in some cases; there are also many varieties of forced supply by steam jets. Air so supplied over the fire to assist in burning the gases is called "secondary air."

Again, the air must be properly mixed with the gases, otherwise even a sufficient supply is useless. In the case of a grate which has been allowed to get bare at some point there is a great rush of air through the bars at the bare spot; this tends to reduce the amount of air drawn in elsewhere, and, as it is too localised to be of any use in itself, the effect of such a burning through of the fire is to make the combustion over the other points less perfect and more smoky, as well as to cool down the furnace and boiler.

The importance of the air supply to a fire being correct in quantity may be brought out in the following way. The chief combustible elements in a fuel consist of carbon, hydrogen, and a little sulphur.

Carbon.—When carbon is burnt in the presence of sufficient oxygen it forms carbon dioxide gas, and every pound of it evolves in the process 14,544 B.Th.U. of heat. It requires a definite amount of oxygen for this purpose, that is, about $2\frac{2}{3}$ lb. of oxygen per pound of carbon. But as the oxygen available is diluted in the air with nitrogen, in the approximate proportion of oxygen 23 to nitrogen 77, the minimum theoretical quantity of air required to burn 1 lb. of carbon completely is 11·6 lb., or approximately 12 lb.

If sufficient air is provided to burn the carbon to carbon monoxide only, the amount of heat given off will be reduced to 4,370 B.Th.U. per pound; thus nearly 70 per cent. of the available heat is left unused.

Hydrogen.—Hydrogen burns to water. A pound requires 8 lb. of oxygen; to get this amount of oxygen we must supply about 35 lb. of air.

Sulphur.—One pound of sulphur combines with 1 lb. of

oxygen to form sulphur dioxide, and to supply the oxygen for the combustion 4·35 lb. of air are required.

The amount of sulphur in coal is so small that we may neglect it in considering the supply of air necessary for combustion. If the fuel to be burnt contains known proportions of carbon and hydrogen, and we call the amount of carbon in a pound of fuel C, and the amount of hydrogen H, the amount of air required for the complete combustion of a pound of the fuel will be 11·6 C + 34·78 H. This makes no allowance for any oxygen present in the fuel; but it is sufficiently accurate for our present purpose.

In ordinary furnaces it is impossible to work with the theoretical minimum quantity of air, and therefore it is usual to take from one and a half to two times the quantity theoretically required. A check is obtained on the quantity of air being admitted by measuring the amount of carbon dioxide in the flue gases. This is very easily done, as there are a variety of standardised instruments suitable for the purpose, some of them self-recording. Thus, when the quantity of carbon in the fuel burnt is known, the percentage of carbon dioxide in the flue gases gives a measure of the amount of air supplied; the percentage should be somewhere in the neighbourhood of 10 to 15 where ordinary coal is burned. If the percentage increases, it indicates that the air supply is being cut down, and there is danger of incomplete combustion with the formation of carbon monoxide; whereas with lower percentages the indication is that there is too much secondary air, and the efficiency of the furnace is injuriously affected.

We may now summarise the more common causes of smoke from coal-fired furnaces :—

1. Cooling of combustion chamber by admission of cold air during the stoking or cleaning of the fires.

2. Too early contact of the gases from the furnace with cool boiler plates or tubes.

3. Too much cooling of the gases by cold furnace walls, etc., when a furnace fire is lighted.

4. Insufficient supply of air over the fire while the volatile gases and tar are being given off.

5. Cooling of the fire by feeding too large charges at a time.

6. Inefficient mixing of the air supply with the gases from the coal.

Domestic Fires

The fire in a domestic grate causes gases and tarry matter to be distilled from the fresh charge of coal. These pass up through cold fuel to escape from the top of the fire, and then either pass away through the chimney unburnt or, when the conditions are suitable, catch fire over the top and burn with a smoky flame. The flame is smoky because it is cooled by the flow of cold air and by contact with the cold sides and back of the grate. We can thus understand why so much tar is found in domestic smoke ; it comes from the yellow condensed vapours which escape unburnt. On the other hand, if the vapours become ignited over the top of the fire they often burn with a smoky flame and produce an excessive amount of carbonaceous or sooty matter. In industrial furnaces, such as those under boilers, there are usually large " combustion chambers " over the fires, which are kept at a high temperature and in which the gases and vapours burn much more completely than over the fire in a domestic grate.

The high proportion of incombustible mineral matter found in the soot or smoke from boiler furnaces is derived from the ash of the coal used. The draught in the chimney stacks of such furnaces is much greater than in domestic chimneys ; particles of ash are carried up with it with greater ease than from domestic grates.

The kitchen range, used for warming the kitchen, for cooking, and for heating water, is a most inefficient apparatus for the purposes for which it is employed, but as a smoke producer it is highly effective. The gases and tarry matter, from which we have seen that smoke is derived, are caused to pass through long tortuous flues, all comparatively cold and certainly a long way below the temperatures required for ignition, so that the flame is never allowed to start, or is extinguished before combustion is complete. The usual horseshoe boiler at the back keeps down the temperature

of the gases which pass under it. A large quantity of coal is burnt to get the heat required, but this is done in such a way that a large amount of smoke is produced, which tends to choke the flues and chimney, and pollutes the air outside.

We may summarise the causes of smoke from domestic fires thus :—

1. Cooling of the gases and condensed tarry vapours below the ignition point by excessive supply of cold air over the fire, and by the cold sides and flues of grates and ranges.

2. Feeding too large quantities of coal at a time, with consequent cooling of the fire and evolution of large volumes of gases which have no chance to burn completely.

Comparison of Domestic and Industrial Smoke

Smoke has been divided into two main types for our present purpose—industrial and domestic. Smoke is produced in far greater quantity per ton of coal burnt in domestic fires than in industrial furnaces. In the former about 5 per cent. of the coal burnt is emitted from the chimney in the form of smoke, while in the latter the smoke is probably 2 or 3 per cent. of the fuel. Domestic smoke differs in its nature from factory smoke, as already shown. The domestic grate or range does not permit of such complete combustion as the boiler furnace, one result of which is that a larger percentage of tar appears in the domestic soot, amounting to between 20 and 40 per cent. of its weight. The tar gives the soot adhesive properties, by which it is enabled to stick to the leaves of plants and the surfaces of buildings in spite of washing by rain. There is little or no tar in the smoke from the industrial furnace used for raising steam.

In spite of the small percentage amount of sulphur contained in fuel, it contributes the most injurious constituent of smoke. This sulphur is emitted in the form of sulphur dioxide or trioxide, and sometimes as hydrogen sulphide, but, whatever be the form in which it is emitted, it rapidly oxidises into the trioxide which, combining with water, forms sulphuric acid.

To get some idea of the great quantities of impurities

poured into the air, the results of a few very simple calculations may be given :—

It may be taken as roughly accurate that, with 1 per cent. of sulphur in the coal, 50 lb. of sulphuric acid are produced per ton of coal consumed.

In the British Isles, excluding Ireland, about 40,000,000 tons of coal are burnt for domestic purposes per year, and if we assume that this coal has at least 1 per cent. of sulphur, which is probably a low estimate, it will produce each year 900,000 tons of sulphuric acid. This sulphuric acid comes down with the rain to poison the soil in the neighbourhood of our cities, and to destroy the fabric of our buildings.

In addition to these 40,000,000 tons, about 100,000,000 tons per year are burnt for industrial purposes, and, calculated on the same basis, this would produce over 2,000,000 tons of sulphuric acid. Thus we have, adding these two figures together, about 3,000,000 tons of sulphuric acid poured into the air over these islands per year.

The sulphuric acid is not necessarily kept out of the atmosphere if visible smoke is prevented, but the smoke particles have the power of absorbing the acid and thus concentrating it wherever the smoke may settle.

The amount of soot which is ejected from our chimneys per year may be taken as approximately 2,500,000 tons. Some of this settles in the neighbourhood of its source, while much of it is carried by the wind over the whole country.

As part of this soot, it may be taken that there are about 500,000 tons of tar.

The above figures will give some idea of the magnitude of the evil due to smoke apart from the waste of material which has an economic value. They will enable us to approach the problem of dealing with the effects of smoke with a better understanding.

CHAPTER IV

THE INDUSTRIAL USES OF SMOKE

In the previous chapter we have set out the causes and origins of the smoke which is poured into our atmosphere to be disposed of in any manner that the unaided forces of Nature may prescribe. It is agreed on all sides that the result is not entirely satisfactory, though it is much better than any one who is unfamiliar with Nature's resources might have thought to be possible. Therein is the crux of the problem of atmospheric pollution. After all, Nature does clear up the mess in a wonderfully efficient manner as a general rule, considering the vast amount that has to be disposed of. It is only on comparatively few days in the year that we are painfully cognisant of the deterioration of our atmosphere by smoke. On many days, even in London, the blue of the sky is visible and there is little apparently to complain of. But as aggregates of houses grow into larger and larger cities the effects of smoke become more and more conspicuous, and public opinion gradually realises that there is a smoke problem of great cities that should have attention.

Nothing can be done to solve the problem, however pressing it may be, without some effort not merely on the part of a few enthusiasts, but by the general public. The difficulty is that, when we come to persons, it is not one's own smoke that fouls one's own atmosphere; there is a natural tendency to wait until other people have shown some activity before bestirring oneself, and that in spite of the fact that in the great majority of cases the smoke is not produced for its own sake, it is merely a by-product of cooking or warming, or driving machinery or some other industrial occupation. Nobody wants the smoke, and, indeed, it is just because they do not want it that they throw it into the atmosphere.

If that were the universal opinion, it would be easier to persuade an influential minority at least to stand by one another and make an effort, even at some sacrifice, to prevent the progress of civilisation destroying its own best productions by smoke. But at the outset we are faced with the difficulty that certain industrial operations require smoke in order to produce a suitable atmosphere; they do not actually consume smoke in their processes, but they employ it to defend their material against injury, and when its protective work is done it must be got rid of; therefore, whatever their neighbours may do or leave undone, they must be allowed to go on making smoke without restriction.

Such an attitude need not paralyse the efforts of cities which are not subject to those exigencies; but it does to a certain extent paralyse general legislation, and is, therefore, a matter for careful inquiry. The case which has been mentioned most frequently at meetings of the Advisory Committee for Atmospheric Pollution is that of the high-carbon steel industry. At the request of the Coal Smoke Abatement Society, Dr. Owens made a special inquiry into that particular aspect of the question, and his report is reproduced here.

Smoke from Steel-making Furnaces

The subject was approached in this way: It was not considered advisable to deal with it from the theoretical standpoint, since there are always many sides of such a question to which prominence could be given, and the value of any statement based upon theory alone is apt to be measured by the eminence of the person who makes the statement.

For this reason another method was adopted, that is, by permission of the owners, steel-making works were visited in which the processes were being carried out which were said to be impossible without the emission of smoke. If, then, even one of such works could be found carrying out the steel treatment effectively without emitting smoke, this would show that smoke emission was not an inseparable accompaniment of such furnaces. In what follows, therefore, a description is given of visits to certain steel works, the names of which are, of course, omitted.

The ground upon which the excuse for smoke from furnaces for the heat treatment of steel is based is that, when heating high-grade steel, especially tool steel, it must be heated in a reducing or smoky

atmosphere, and this is especially necessary when dealing with small pieces of steel exposing large surfaces, and applies particularly to wire and sheet work of high carbon steel. This is really the basis of all the excuses for smoke from steel treatment furnaces, and, however true this statement is—and it cannot be controverted—it applies only to the necessity for smoke in the furnaces, and does not carry with it any necessity for emitting smoke from the stack. It is essential that, when treating high-carbon steels, such as are used for files, tools, and hack saws, the surface of the steel should not be decarburised. The teeth of hack saws and of files are formed so that the original surface of the steel forms the cutting edge of the tooth, and, therefore, if this surface has been softened or decarburised, the edge will be soft and the tooth will lose its cutting property very quickly.

Furnaces Inspected

The following furnaces were inspected in operation :—

1. Coal-fired furnaces, for—
   (*a*) Annealing circular saws.
   (*b*) Reheating sheets of high-carbon tool steel for rolling, that is, steel for hack saw blades.
   (*c*) Reheating steel castings.
   (*d*) Heating high carbon steel billets for rolling.
   (*e*) Annealing steel wire.
   (*f*) Heat treatment of alloy and carbon steel.
2. Town gas-fired furnaces, for—
   (*a*) Annealing tool steel.
   (*b*) Hardening and tempering alloy and carbon steel.
3. Producer gas-fired furnaces, for—
   Annealing steel castings.
4. Pulverised coal-fired furnaces.

1. Coal-fired Furnaces.—In all coal-fired furnaces observed a reducing atmosphere was obtained in the furnaces by having an excess of smoke ; when the furnace door was open, the furnace was seen to be full of smoke and smoky flame, but this smoke was incandescent, a dull red. This was true for all furnaces observed, but, and this is the important point, it was not true that smoke was emitted from the chimney stack in quantity from all these furnaces. For example, in one row of eight furnaces reheating high carbon steel for rolling which the author had under observation, and in which the smoky reducing flame existed in the furnace itself, there was no visible smoke from the chimneys except from one, which was being fired. Later on smoke issued from some of the others as they were fired. The author was informed by the owner of the works that the only time his furnace emitted smoke in any appreciable quantity was when being fired. Thus it is evident that it is possible to obtain the necessary reducing atmosphere with plenty of smoke in the furnace and still not to emit that smoke from the top of the

chimney stack. In all the furnaces now referred to the draught was regulated by a damper or lid on the top of the chimney stack, which damper was adjusted with the utmost care so as to reduce the draught to a minimum. For example, in the furnace referred to the diameter of the chimney was about 22 inches inside ; the cap or damper was, when working, about $\frac{1}{8}$ to $\frac{1}{4}$ inch clear of the top of the chimney, and this distance was adjusted to within $\frac{1}{16}$ inch to get the most suitable conditions.

It will be noted in what follows that other coal-fired furnaces in which the draught was regulated from below produced large quantities of smoke.

Size of furnace is also of great importance from the point of view of smoke production, as if the furnace is large enough to prevent undue cooling when the steel is introduced there is less likelihood of smoke. The furnace, in fact, should provide a reservoir of heat which can be drawn on to heat the cool steel. If the furnace is too small it will be unduly cooled and combustion interfered with when the steel is introduced. The author was informed by the owner of the furnaces, which have been referred to above as being smokeless except when being freshly fired, that, for a furnace carrying 1 ton of steel, a grate area of about 10×5 feet should be allowed. There was nothing very special about the construction of the furnaces referred to ; they had open grates and direct connection between the furnaces and the chimney stacks.

Coal-fired furnaces for annealing and hardening steel wire were subsequently inspected. In this case they consisted of a central furnace or combustion chamber to receive the steel, which chamber had a solid bottom, and the furnaces proper to receive the coal were at each side, the flues being led into the central chamber and the draught regulated by fire doors and by dampers over the furnaces.

In this case a large amount of smoke was produced at all times, and it was much worse immediately after stoking, and worst of all during the dinner hour, since the fires were made up by the men to last an hour. These furnaces were of the open-hearth wire annealing type.

The author then saw in operation certain coal-fired furnaces used for heating high-speed and carbon steels, and in this case the steel bars were embedded in sand in boxes before placing in the furnace. A reducing atmosphere and a very smoky flame were kept in the furnace, and out of three furnaces in operation at the same time the chimneys of two were smoking badly, while the third was producing very little smoke from the chimney, although it was being heated up and the furnace itself was full of smoke.

2. **Furnaces fired by Town Gas.** In all these furnaces which the author saw in operation the gas was burnt inside the furnace in a luminous flame, and the air supply so adjusted as to give a smoky flame. The inside of the furnace was filled with smoke which was incandescent, that is, a dull red, and very similar in appearance to the smoke in the coal-fired furnaces. In spite, however, of the

existence of the smoke and the reducing atmosphere in the furnace itself, no smoke was visible from the top of the chimneys. The furnaces which were inspected worked at a temperature of about 800° to 830° C., and the pressure of gas used was 3 to 3½ inches, and of air 1½ inches. They were used for hardening and tempering high-grade steel. The author was informed by one of the engineers in charge that gas was preferable to coal from the point of view of handling and of controlling temperature, that it performed the work required without injury to the steel, and the only objection was its cost. He was subsequently informed by the works engineer at the same place that the cost of town gas for hardening and annealing steel was about three times that of coal ; the quantity of each used for furnaces giving a temperature of 1,100° C. approximately was as follows :—

(*a*) Coal used per ton of steel . . 2½–3 cwt.
(*b*) Town gas used per ton of steel . 6,000–7,000 cubic feet.

It was stated by this engineer that town gas produced more scale upon the steel than coal, the cause of which he could not explain ; and, further, he stated that the calorific value of gas was not sufficiently constant, and this produced injurious effects, the reason for which he did not know. He said that for thin sheet steel coal is best, as gas is liable to blister the sheet, suggesting as an explanation that there is more smoke in a coal-fired furnace than in a gas-fired one, which, according to the author's observations, was true. An objection to the furnace fired by town gas was given subsequently at another works, to the effect that the furnace is not uniformly heated, but has a hot and cold side ; this objection, however, is not inseparable from the use of gas as a heating agent, but arises rather from the fact that the gas flames in the furnaces he referred to were all at one side, and such an objection would, of course, be overcome, and indeed has been, in furnaces burning the gas on both sides. The author formed the opinion that the only real objection to the use of town gas for the heat treatment of steel was its cost.

3. **Producer Gas-fired Furnaces.**—These furnaces were run from Morgan producers using bituminous coal, and were in operation for annealing steel castings. They produced no smoke from the chimneys, and the engineer in charge of the works stated that they had found the producer gas-fired furnaces cheaper in operation than coal-fired furnaces for continuous work, but for intermittent work the stand-by losses with producers made them more costly than coal-fired furnaces. Thus in the same works producer gas-fired furnaces were used for annealing steel castings, while coal-fired furnaces were used for heating these castings for straightening. Gas was used in the same works for manufacturing steel in crucibles. The works engineer stated that in a new works there would be no difficulty in avoiding smoke if suitable furnaces were installed, and that the real difficulty in avoiding smoke lay in the necessity for substituting new plant for old.

4. **Pulverised Fuel Furnaces.**—The author saw a pulverised fuel furnace in use for heating billets for forging. This gave rise to no smoke, and as it is very similar in operation to a gas-fired furnace, it is referred to at this stage. It will be observed that the chief difficulty in avoiding smoke from the coal-fired furnaces is when stoking or adding new fuel, or when heating up a cool furnace. Thus the use of pulverised fuel, which makes it unnecessary to add a large amount of fresh fuel at long intervals and gives a continuous feed instead, similar to a gas-fired furnace, is one possible solution of the smoke problem, although no pulverised fuel furnace for reheating or annealing high-class steel was seen. The use of pulverised coal involves, however, new furnaces and a costly plant for powdering and feeding the coal; hence it is open to the same objection as producer gas.

Conclusion

The results of the investigation are summarised as follows :—

(*a*) While a smoky flame is essential in the heat treatment of high-class steels, it does not appear to be essential that smoke should be emitted from the chimney in any quantity. This is shown by the fact that some coal-fired furnaces emit little or no smoke from the stack, while others emit large quantities, although doing practically similar work, and, further, by the fact that gas-fired furnaces produce a similar smoky flame and reducing atmosphere without the emission of smoke from the stack.

(*b*) The only real objection to the use of town gas for steel-making which is of great importance is its cost as compared with coal.

(*c*) The use of producer gas provides a solution of the smoke problem, and is more economical than coal. It is, however, not practicable for very small works, and it involves considerable capital expenditure for plant.

(*d*) Since the production of excessive smoke usually follows the periodical firing of fresh coal, as in the case of boiler furnaces, it seems that there is a case for the introduction of some form of continuous mechanical feed of coal for steel heating furnaces. The excessive emission of smoke from the chimney after firing is not essential to prevent injury to the steel, since a suitable atmosphere in the furnace is obtainable when practically no smoke is issuing from the chimney.

(*e*) The problem of smoke production from coal-fired furnaces for the heat treatment of steel is one calling for energetic research and experiment, as there is no doubt great improvements might be made without inflicting any hardship and with little expense.

Finally, the real and fundamental objection to the extended use of smokeless or nearly smokeless furnaces is the fact that it would mean alteration to many existing plants, and it is felt that this would, under the present conditions of industry, handicap the steel trade if such alterations were insisted upon.

CHAPTER V

THE ECONOMIC ASPECT

The Effects of Smoke and other Atmospheric Pollution upon Fabrics, Building Materials, Metals and Plants

It is difficult, if not impossible, to assess the full economical effect of smoke, but that it is of great importance is very evident when we consider the number of directions in which its effects are felt.

Effect on Fabrics, Etc.

Apart from the dirt deposited from the air making it impossible to keep fabrics clean, such as clothes, curtains, carpets, and so on, there is a definite deterioration due to the action of the sulphur-laden smoke. It has the effect of rotting such things as curtains and blinds which are continuously exposed.

The amount of energy which is spent in cleaning is very great, and the proportion which is directly due to smoke is high. This is expressed in the laundry bills in cities and their immediate neighbourhood. It is also felt by shops and stores in the accounts for cleaning and renewing injured articles. Curtains, which in Aberdeen are washed once a year, have to be washed once a fortnight in Manchester.[1]

There is a further loss arising from the necessity for artificial lighting, which is due to the obstruction of daylight by the smoke. There is always some obstruction necessitating a little earlier lighting in smoky cities than in the country, while under certain conditions artificial lighting

[1] Air Pollution Advisory Board: Manchester. "The Black Smoke Tax," 1919.

has to be provided during the whole day when the smoke accumulates in the form of a thick haze at the level of the houses or as a pall overhead. Examples of both such conditions have been already referred to in Chapter II.

Buildings

The corrosive effect of a smoke-laden atmosphere upon metals is too well known to require emphasis here. The sulphur contained in the coal is sent into the air in the form of sulphurous or sulphuric acid, and is probably almost immediately all converted to the sulphuric state by oxidation. The acid may combine with ammonia to form ammonium sulphate, and whether in that form or in the form of sulphuric acid, it has a marked corrosive action.

Building stones, composed mainly of limestone, tend to become "sulphated" when exposed to a smoke-laden atmosphere, that is, to have the calcium carbonate which forms the limestone converted into sulphate. When this happens there is an increase of volume and the swelling bursts the stone, so that the surface flakes off. When the stone is a magnesian limestone, the effect is even worse, as magnesium sulphate is then formed, and this, being very soluble in water, is washed away by the rain and the stone becomes disintegrated.

The proportion of calcium carbonate in a stone need not be a measure of its liability to attack. Sandstones which have the particles cemented together by calcium carbonate show the effect in a marked degree, the cementing matter being disintegrated as described above. The attack on buildings is not limited to smoky cities, but extends far into the surrounding country, so that the disintegration and breaking down of the stone is found very well marked in such places as Hampton Court Palace, Windsor Castle, Rievaulx Abbey in Yorkshire, Tintern Abbey, and many other buildings far removed from great cities.

There is nothing to be surprised at in this, as the wind carries the smoke and the sulphur impurities over the whole country, and under certain conditions of weather already

referred to, the drift of smoke may be fairly concentrated; such conditions are found during anticyclones with a light wind drift and an inversion of the vertical temperature

Effect on Buildings

Fig. 4.—Weathering at Buckingham Palace. Bath stone in pediment of East Gallery, Royal Mews. Surface facing south-west, about 40 feet above ground.

gradient, during which the impurities are held in a layer near the surface of the ground.

The cost of repairing buildings thus affected is very heavy

and has been estimated as amounting to £120,000 per annum for official buildings alone.[1]

Effect on Buildings.

Fig. 5.—Weathering at the Tower of London, middle tower. Sooty incrustation on Caen stone. The clean portion is Portland stone. Photograph taken May 12th, 1920.

The effect of smoke on buildings, apart from the deposit of soot which blackens and disfigures the surface, may be

[1] Sir Frank Baines, Director of Works, H.M. Office of Works: in the Report of the Conference on Smoke Abatement, Manchester, 1924.

summarised as due to the corrosive effect of sulphur produced from coal, converting the calcium carbonate of lime-

Effect on Buildings.

Fig. 6.—Weathering at Chelsea Hospital. Red brick pier showing exfoliation. Photograph taken May 10th, 1920.

stones into sulphate, which by swelling disintegrates the stone, the same corrosive effect being produced on all iron-

work which is not constantly cleaned and painted. It is found, for example, that corrugated iron buildings have a life of only a few years in or near large cities.

In London, the Houses of Parliament, Westminster Abbey, the Tower of London, St. Paul's Cathedral, Buckingham Palace, and the Law Courts are only a few of the chief buildings which have badly deteriorated by the action of smoke.[1]

Effect on Buildings.

Fig. 7.—Weathering at Hampton Court Palace. Portland stone balusters on north side of Fountain Court. South aspect, about 40 feet above ground.

Ordinary coal may contain 2 or 3 per cent. of sulphur. When this is burnt, most of it passes out of the chimney as sulphur dioxide (SO_2) or sulphur trioxide (SO_3). It has already been noted that probably SO_2, in the presence of water, is very rapidly oxidised into SO_3, and the latter, with the water in the air, forms sulphuric acid (H_2SO_4).

[1] Figs. 4, 5, 6, 7, which represent some typical examples of the weathering of stonework and brickwork of public buildings, are reproduced from the original photographs by kind permission of Sir Frank Baines, C.V.O., C.B.E., Director of Works, H.M. Office of Works and Public Buildings.

If we assume 75 per cent. of the sulphur passes out with the smoke, the balance remaining in the ash, then for every ton of coal burnt there may be produced in the air approximately 50 lb. of sulphuric acid for each 1 per cent. of sulphur present in the coal. It is evident, therefore, that enormous quantities of sulphuric acid are formed in the air every day. We can get some idea of what happens in a city like London, for example, which consumes about 17,000,000 tons of coal per year. This is all burnt in about ten hours of each day, and means that every hour of the day between 200 and 300 tons of sulphuric acid (H_2SO_4) are formed in the air over London. It is not to be wondered at that, when the smoke accumulates to form a dense haze or so-called "smoke fog," the eyes smart and the nose and air passages are irritated.

The acid thus formed is brought down to a great extent by rain as well as by the settling of particles of soot and fog; thus surfaces of buildings and plants are exposed to an acid rain. The 200 or 300 tons of acid would convert the same weight of calcium carbonate ($CaCO_3$), *i.e.* limestone, into sulphate. The rapid decay of buildings exposed to city air need, therefore, occasion no surprise.

Vegetation

Smoke acts on vegetation in several different ways, which may be summarised as follows :—

(*a*) The sulphur impurities poison the soil so that growth is impeded or even made impossible.

(*b*) The soot falls on the green leaves, cutting off sunlight which is necessary for the formation of the vitamines now recognised as essential for life. The factory for making vitamines is the green leaf.

(*c*) The suspended smoke in the air cuts off sunlight and reduces daylight, and thus acts in this respect in the same way as the layer deposited directly on the leaves. In the winter fully 40 to 50 per cent. of the sunlight may be thus cut off, and as much of the diffuse daylight.

(*d*) The stomata or minute pores of leaves, by means of which they absorb carbon dioxide from the air to convert

it into sugars, starches or other carbohydrates, are plugged up by the soot. In this connection it is important to note that the soot from domestic fires contains a large amount of tarry matter—20 to 40 per cent.—which causes it to adhere to the leaves and prevents the rain from washing it off.

(*e*) Various ferments or enzymes found in soil and plants are largely responsible for the chemical changes which take place in plants, and these are found to be profoundly inhibited by the action of smoke. Some of these enzymes play a vital part in the production of colours, and it is found that flowers grown in air polluted by smoke lose their colours to a great extent, especially red and blue flowers, which become very pale or white after a few years in a smoky city.

The result is that in and near smoky cities all kinds of vegetation suffer. The evergreens suffer most, since their leaves are exposed to the smoke of winter as well as summer.

One may venture to surmise that even in the depths of the country the mysterious failures of crops may sometimes be due to prevalence of such meteorological conditions as favour the concentrated drift of smoke over the affected crops.

Curious indirect effects may also happen. It has been found [1] that the continuous rain of acid upon soil tends to neutralise the free lime, forming calcium sulphate, which is washed out, making the soil poor in lime. Grass and hay grown on such soil are poor in lime, and cows fed on them give milk having a low ratio of lime to phosphoric acid. The ratio in normal milk should be 1 : 1, and rarely below 1 : $1\frac{1}{4}$, whereas milk from Garforth, seven and a half miles from Leeds, showed a ratio of 1 : 2. Lime is essential to bone formation : hence at the end of this long string of connected causes and effects we find children suffering from rickets.

The more direct effects of smoke upon health are considered in a later section of this Chapter, p. 63. In the meantime we turn to the question of the cost of smoke.

[1] A. G. Ruston : Minutes of Evidence, Departmental Committee on Smoke and Noxious Vapours Abatement, 1920.

The Cost of Smoke

In 1912 an attempt was made at Pittsburg to ascertain the cost of the smoke nuisance to the city, that is, the excess cost due to the sum of the various causes already referred to, beyond what it would have been in the absence of smoke. The method of investigation was by the circulation of "schedules" to storekeepers and others asking them to prepare estimates, based on their experience, of the extra cost caused by the smoke pollution of the air.

The following table shows the results obtained [1]:

	£
1. Cost to smoke-maker :—	
(*a*) Imperfect combustion	330,595
2. Cost to individual :—	
(*a*) Laundry bills	326,087
(*b*) Dry cleaning bills	163,043
3. Cost to household :—	
(*a*) Exterior painting	71,739
(*b*) Sheet metal work	219,130
(*c*) Cleaning and renewing wallpaper	119,565
(*d*) Cleaning and renewing lace curtains	78,261
(*e*) Artificial lighting	18,261
4. Cost to wholesale and retail stores :—	
(*a*) Merchandise	358,696
(*b*) Extra precautions	97,826
(*c*) Cleaning	163,043
(*d*) Artificial lighting	141,304
(*e*) Department stores	38,043
5. Cost to *quasi*-public buildings :—	
(*a*) Office buildings	19,565
(*b*) Hotels	4,783
(*c*) Hospitals	11,956
Total	£2,161,987

The final result of this investigation indicated that the cost per head of the inhabitants of Pittsburg amounted to $20 per annum. It is important to note here that this estimate does not include anything for losses due to injury to health or what is referred to in the Bulletin as "the disagreeableness of it all." However, we may accept the table as a useful and sufficiently accurate indication of the losses due to smoke.

[1] Mellon Institute, University of Pittsburg, Bulletin No. 4. The figures have been converted to pounds at the rate of 4·6 dollars to £1.

There is a simple way in which we can apply these figures to London without great probability of error. During the year 1912–13, covered by the investigation referred to, the average sootfall in Pittsburg, taken from twelve different stations, amounted to 1,031 tons per square mile.[1] The average sootfall for London for the year ending March 31st, 1924, was 288 tons per square mile. We may fairly assume that the cost per head of the population will vary directly as the sootfall. The cost per head in London, arrived at in this way, would be $5·5, or 24*s*. per annum. If we take rate of cost over the population of Greater London, say, seven million people, we have the colossal figure of £8,400,000 per year.

It is of interest here to note that, in his paper entitled "London Fog and Smoke," the Hon. F. A. Rollo Russell in 1899 estimated the annual cost of the smoke nuisance to London at £1 per head of the population.

In 1918 an investigation was made into the cost of smoke in Manchester, based on the same method as that applied at Pittsburg.[2] The result of the investigation was the same figure, that is, £1 per head of the population, as being "well within the mark," and the total cost per annum to Manchester of the smoke was estimated to be at least £750,000.

If we examine the question in the same way as for London, that is, basing the cost upon the Pittsburg investigation, we find that the cost per head for Manchester is 30*s*.

Thus the average deposit, based on two stations in 1917–18 in Manchester was 360 tons per square mile per annum. The cost to Manchester would, therefore, be $\frac{20 \times 360}{1031}$ dollars, or 30*s*. per head.

It is not satisfactory to assume that the cost in all big cities due to smoke pollution is the same, since the amount of smoke in different places varies very considerably, but

[1] Bulletin of the Mellon Institute, University of Pittsburg, No. 8, p. 22.

[2] Pamphlet issued by Manchester Air Pollution Advisory Board, entitled "The Black Smoke Tax," 1919.

if we deal with them on the lines above indicated we may arrive at a simple method of estimating the cost per head. The method, in its simplest form, may be set out as follows :—

The Pittsburg estimate, at a time when the measured sootfall was 1,031 tons per square mile, amounted to $20 or 87*s*. per head, taking 20*s*. as the equivalent of $4·6. Let us call the sootfall in tons per square mile per annum in any city S ; then the cost per annum per head of the population will be :

$$\frac{87\ S}{1{,}031} \text{ shillings, or simply } \frac{S}{11{\cdot}9} \text{ shillings.}$$

Applying this to London, we find the cost per head for the year 1924 would be :

$$\frac{288}{11{\cdot}9} = 24s. \text{ per head,}$$

and for Manchester for the year 1917–18 :

$$\frac{360}{11{\cdot}9} = 30s. \text{ per head.}$$

These figures, while making no claim to great accuracy, give a reasonable idea of the cost of the smoke nuisance, and it will be seen that in a country such as England, where there are cities having a heavier sootfall than either London or Manchester, the direct financial loss incurred by the country arising entirely from smoke production is enormous ; its saving would make a considerable addition to the revenue.

Losses Due to the Coating of Boiler Plates or Tubes with Soot [1]

Soot is a very bad conductor of heat, and hence, if a boiler plate is coated with it, the rate of heat transfer through the plate is reduced. The actual loss in conductivity due to such a layer of soot appeared to be of sufficient importance to justify special experiments on the subject. In order to carry out these experiments, a calorimeter was

[1] International Smoke Abatement Conference, 1912. "Wasteful Power Production," by J. S. Owens.

prepared consisting of a small polished metal vessel holding about 450 c.c. of water; this was fixed inside a larger vessel so that the bottom projected through that of the larger vessel, and the sides were surrounded by an air jacket. Both vessels were provided with lids, and through these projected a thermometer, the bulb of which was in the inner vessel; also the handle of a stirrer, which was intended to mix the water in the inner vessel to a uniform temperature. The exposed bottom of the inner vessel could be coated with soot to any desired thickness.

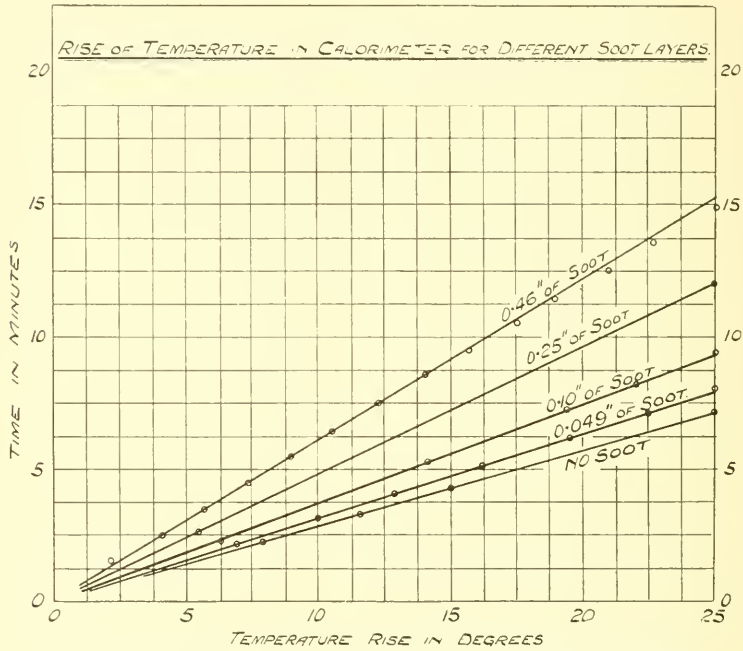

FIG. 8.—Observations of the warming of water through different layers of soot.

The method of using the instrument was as follows:—

A layer of soot was placed on the bottom of the inner vessel. This was done by making soot from a boiler furnace into a paste with water, so that it adhered to the vessel; the layer was then carefully dried. The next step was to place exactly 400 c.c. of water in the inner vessel and replace the lids; the calorimeter was then placed on an asbestos sheet with a circular hole cut in it through which the bottom of the inner vessel projected, and in which it fitted exactly. The function of this sheet was to protect the bottom and walls of the outer vessel from the heat. A paraffin lamp was next

placed under the calorimeter, with its flame adjusted to a steady height; and as soon as the temperature of the water reached 55° F. the time was noted; subsequently the temperature was noted at intervals of about a minute until it reached 80° F., when the time was again noted. The soot layer was then measured by a micrometer or depth gauge, and afterwards stripped off and the bottom cleaned, when the vessel was again filled with 400 c.c. of water, replaced on the stand over the flame, and the time and temperature noted as before.

Thus all conditions were kept as constant as possible in the two

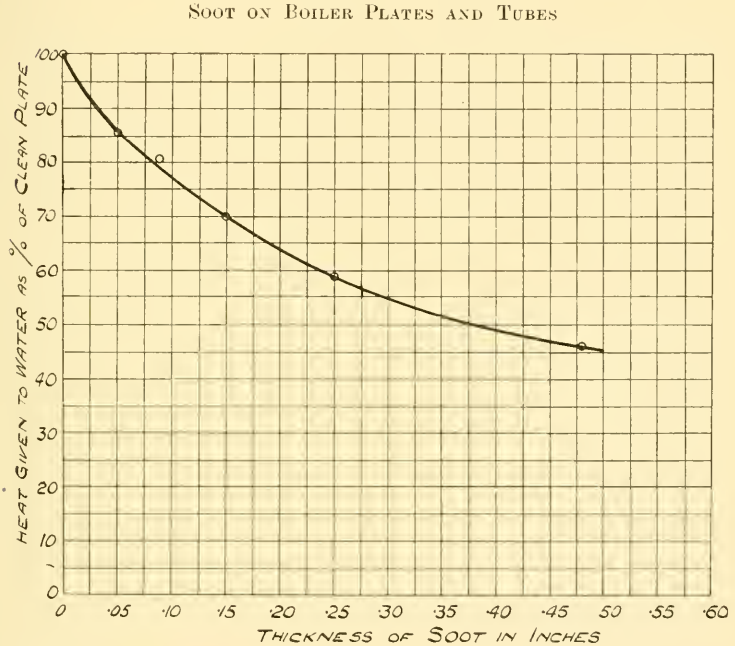

Fig. 9.—Curve showing the effect of soot upon the passage of heat through a metal plate.

experiments, with the sole exception that in one the heat had to pass through a layer of soot, and in the other only through a clean plate, in order to reach the water. The experiment was repeated for different thicknesses of soot, and the results collected and analysed.

The accompanying curves (Figs. 8 and 9) show graphically the influence of the soot in obstructing the flow of heat. The same results are given in the following table, in which the amount of heat passed

into the water in a given time is expressed as percentages of that passing through the clean unsooted plate :—

Thickness of soot layer. Inches.	Rate of heat transfer as a percentage of that through clean plate.
0·0	100
0·05	86·3
0·10	77·4
0·15	70
0·20	64
0·25	59
0·30	55
0·35	51·8
0·40	49
0·45	46·8
0·50	45·3

These values were found by drawing a fair curve through the experimental values and interpolating. In the curve (Fig. 8) the experimental values are shown. The percentages were obtained thus :—

Since the difference of temperature inside and outside the calorimeter was the same for all experiments, the rate of heat transfer should vary inversely as the time required for the same rise of temperature. Suppose, as in the experiment with a soot layer 0·049 inch thick, the time required to raise the temperature from 55° to 80° F. was with the clean plate 6·83 minutes, and with the soot-covered plate 8 minutes, then, calling the rate of transmission through the clean plate 100, and the rate through the sooty plate R,

$$\frac{100}{R} = \frac{8}{6{\cdot}83}$$

or

$$R = 85 \text{ nearly ;}$$

the rate through the sooty plate was only 85 per cent. of that through the clean plate.

In these experiments the layer of soot was formed by making a paste of soot and water ; this is not, strictly speaking, similar to a layer of soot deposited by smoke, but, owing to its greater density, it probably conducted heat better, so that the results are likely to appear more favourable than they really are in practice when boiler tubes or plates become covered by soot. In the latter circumstances it has been shown that there is a rise in temperature of the flue gases due to the diminished absorption of heat by the boiler. It will be seen from the table and curves that the loss which may result from soot deposit on heating surfaces is a very great one, amounting to 15 per cent. of the fuel for a layer of soot only one-twentieth of an inch thick.

The Effects on Health

Smoke reacts on the health of human beings in a variety of ways, and it is difficult to say which is the most important.

Loss of Sunshine

We depend on sunlight for our life, both directly in its physiological action on the body and indirectly, as it enables plants to produce our food. The vital importance of sunlight has been more clearly brought out in recent years, and the evil effect of any condition which reduces our supply needs no emphasis.

Let us consider to what extent smoke affects the quantity of sunshine and daylight in our great cities.

Cohen and Ruston [1] have measured the effect of smoke on daylight by exposing, in Leeds, a mixture of 50 c.c. of a 1 per cent. solution of potassium iodide and 10 c.c. of dilute sulphuric acid for twenty-four hours. The liberated iodine was measured by titration with sodium thiosulphate. They concluded that "fully 40 per cent. of the light was shut out from the industrial area." The results showed that there was a striking relation between the soot deposited and the amount of daylight received.

In Sheffield the amount of sunshine received at Weston Park was compared with that received at Attercliffe, about three miles away, and it was found that: "During three winter months, when every ray of sunshine is most precious to town dwellers, Attercliffe receives only about one-half the amount that falls to the Weston Park district." [2]

The cause of this serious loss is evident when the amounts of deposited impurity for the two places are compared. During the three months November, December, and January, 1914–15, the total deposits measured were as follows :—

Weston Park	99
Attercliffe	167

In Manchester it has been shown that about 50 per cent.

[1] Cohen and Ruston: "Smoke: a Study of Town Air," Arnold, 1912.

[2] Report of the Investigation of Atmospheric Pollution. City of Sheffield. 1914–15, by Prof. W Palmer Wynne.

of the winter sunshine is lost, while the loss of ordinary daylight is about the same. Experiments made in 1913 by Mr. E. Ardun, under the direction of Dr. Fowler,[1] showed that at the Davyhulme Sewage Works the light received from 10 a.m. to 4 p.m. during November averaged 2·36 times that received at the School of Technology, in the centre of the city. Davyhulme is about five miles west-south-west from the School of Technology, and ranks as country. The deposit of total impurities at the two places for the winter months October to March, 1914–15, was as follows, in tons per square mile :—

School of Technology. Mean monthly deposit 44

Davyhulme. Mean monthly deposit . . 29

Turning now to London, the following table was given by Mr. Lempfert to the Smoke Abatement Conference, 1912, for

Duration of Sunshine at "Town" Stations expressed as a Percentage of the Duration at "Country" Stations

	City and Westminster compared with Oxford, Cambridge, Marlboro', Geldeston.		Kew Observatory, Richmond, compared with Oxford, Cambridge, Marlboro', Geldeston.		City and Westminster compared with Kew Observatory.	
	Winter.	Summer.	Winter.	Summer.	Winter.	Summer.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
1881–1885	17	83	85	97	20	84
1886–1890	29	85	89	96	32	87
1891–1895	32	95	83	102	39	94
1896–1900	35	89	97	103	36	86
1901–1905	32	93	88	104	37	89
1906–1910	38	92	81	99	46	92
1911–1915	41	97	86	101	47	96
1916–1920	45	95	86	99	53	96

December and January are taken as representing winter, and June and July as representing summer.

the sunshine recorded in London and at country stations. It has been brought up to date by figures supplied by the

[1] Report of Sanitary Committee of City of Manchester, 1915.

Director of the Meteorological Office. The duration of sunshine in London expressed as a percentage of the duration

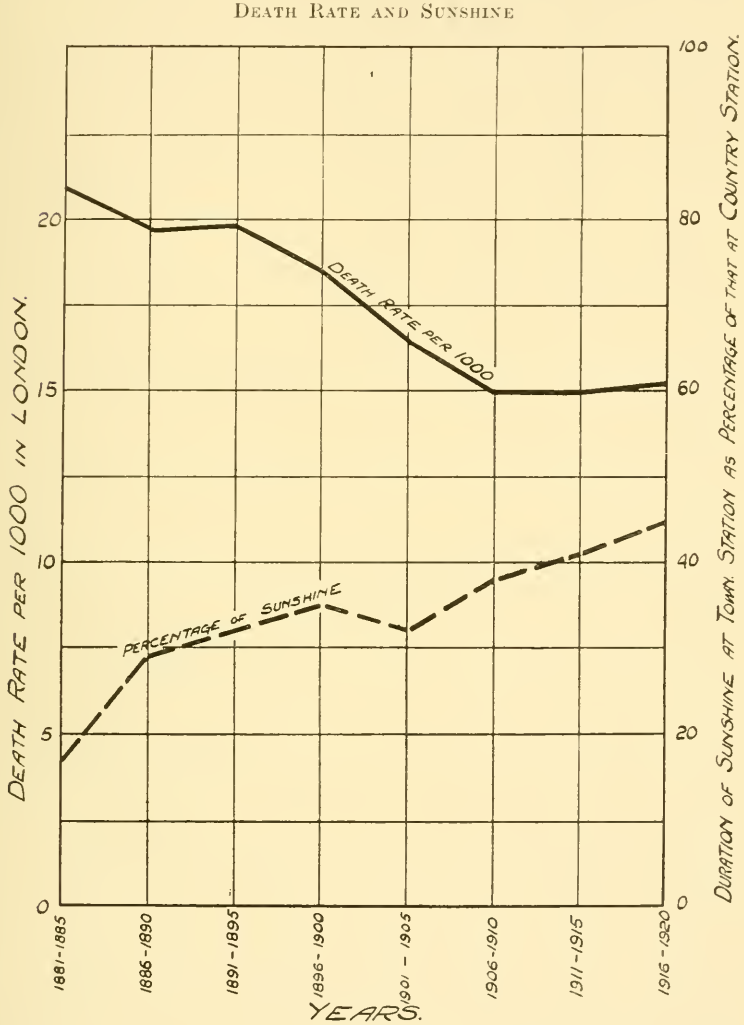

Fig. 10.—Curves for comparing death rates in the administrative county of London with records of sunshine in the forty years, 1881 to 1920.

at country stations is given for groups of five years from 1881 to 1920. It will be seen that in the five years 1881–85

Fig. 11.—Curves for comparing death-rates in the administrative county of London with annual deposits of impurity during the eight years, April, 1915, to March, 1923.

only 17 per cent. of what may be called the expectation of sunshine in London was received in the winter, and 83 per cent. in the summer; whereas in the period 1916–20

45 per cent. was received in the winter and 95 per cent. in the summer.

As illustrating the effect at different times of the year, a further table is given showing the sunshine at London stations expressed as a percentage of mean values for country stations.[1] In this table the country stations compared with London are Oxford, Cambridge, Geldeston, Southampton and Rothamsted, the London station being at Westminster. The figures are derived from observations extending over twenty years.

Sunshine at London Stations expressed as Percentages of Mean Values for Country Stations on the Average of Twenty Years

	Jan.	Feb.	Mar.	Apr.	May	Jun.	
Westminster .	38	45	55	70	82	81	
	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year.
Westminster .	83	86	78	65	46	29	64

These figures speak for themselves; the great loss during the winter is evident. It is satisfactory, however, to see that the amount of sunshine received by London has gradually increased since 1881.

Sunshine and Public Health

The curve shown in Fig. 10 is prepared from the sunshine figures referred to above for the period 1881–1920, and the death rate figures for London for the same period. The latter figures have been supplied through the courtesy of the Registrar-General, and they have been converted into averages for the quinquennial periods for which the sunshine records are given. These averages are plotted on the same base as the sunshine in Fig. 10.

The remarkable way in which the duration of sunshine has increased while the death rate has decreased during the period considered is striking. It is not to be supposed that these two are related as sole cause and effect; there are many factors governing the death rate, but the curious

[1] London Fogs. Report of the Meteorological Council, 1904.

relation shown in the figure suggests that one of these factors is the amount of sunshine received.

From the above few data the magnitude of the smoke evil can be gathered, and the fact that it is preventable to a great extent may be inferred from the table already referred to, which brings out the increase in the sunshine received in London within the period of forty years.

In Fig. 11 another curve is shown. In this the annual total deposit in London in tons per square mile is plotted on the same base as the death rate for the years 1915–23. The figures for the deposit show a steady reduction in amount, which is reflected also in the death rate figures; the abnormal peak in 1918 was due to the influenza epidemic. Apart from this, one cannot help being struck by the fact that a reduction in deposited impurity was accompanied by a reduction in death rate. Here, again, as explained with regard to the increase of sunshine, we cannot suppose that the reduction in deposit was the only cause of the reduction in death rate. There are many other factors involved, but the relation exhibited is certainly most suggestive.

It is, in fact, not easy to show a direct connection between smoke pollution and health by means of statistics. The Departmental Committee on Smoke and Noxious Vapours Abatement, in their Interim Report in 1920, state :—

"Statistical evidence shows a close relation between the death rate and the atmospheric conditions: the number of deaths from pulmonary and cardiac diseases is shown to increase in direct proportion to an increase in the intensity and duration of smoke fogs. The cause underlying the high mortality in towns, which is known to follow in the wake of a fog, must operate continuously, though in a lesser degree, on the health of an urban community."

London, in spite of its smoke pollution, has now a very low death rate, as shown by the Registrar-General's returns. It must, however, be kept in mind that a large proportion of the population officially credited to London live outside the city, and come up daily to business. Such people would not die in London, and the effect of this practice is to reduce somewhat the London death rate.

An attempt was made in 1920 by the Advisory Committee

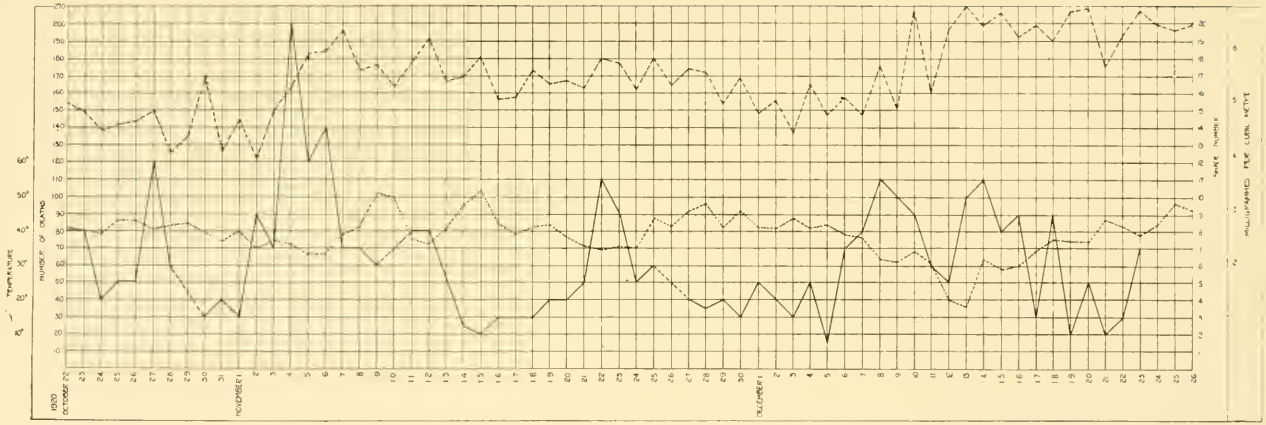

Fig. 12.—The full line represents the maximum measure of suspended impurity in the atmosphere of Westminster, 47 (Victoria Street), on each day, October 22nd to December 23rd, 1920. The line of dots shows the minimum temperature of the air. The line of dashes shows the number of deaths registered in London for the same days. The scales of enumeration are indicated on the sides of the diagram. On the left-hand side is first the scale of temperature, two squares to ten degrees between 10° F. and 60° F., and next thereto the number of deaths, each square indicating 10; on the right-hand side, the shade number of the maximum impurity for the day, and next thereto the equivalent amount of impurity in milligrammes per cubic metre.

on Atmospheric Pollution, in conjunction with the Registry Department of Somerset House, to find the relation, if any, between daily death rate and suspended impurity in London. The figures used for the purpose were the maximum impurity for the day; and to compare these with the daily death rate, curves were plotted showing the relation between these two [1] (Figs. 12, 13).

It was hardly to be expected that a close relationship would be observable, since the effect of abnormally high impurity at any time might not show itself in the death rate for a considerable period. In spite of this, however, there was some relation to be detected, although indicating that the periods of high death rate followed periods of high impurity. The indications were not, however, very consistent. It must be remarked, moreover, that this relationship may be more apparent than real, since abnormally high impurity in London usually coincides with very low temperature. A curve of minimum temperature plotted with the other two indicated a close inverse relation between death rate and temperature.

The deaths plotted in this case included deaths from all causes, while it was hardly to be expected that diseases other than those of the respiratory organs would be affected by impurity. An attempt was then made to separate the respiratory diseases from others, and the daily deaths from these diseases were plotted against the maximum impurity for the day. An indication of some relation was again observable; it was not very marked, nor, indeed, could this be expected, for the reason already referred to.

A more hopeful line of inquiry, though somewhat difficult to follow up, is the relation between annual death rate in different cities and the quantity of impurity in the atmosphere.

There are, however, so many other factors affecting death rate, such as sanitation, water supply, and so on, that it is almost impossible to disentangle them, especially as only a very small number of cities take records of the degree of impurity of the atmosphere due to smoke.

[1] Seventh Annual Report, Advisory Committee on Atmospheric Pollution.

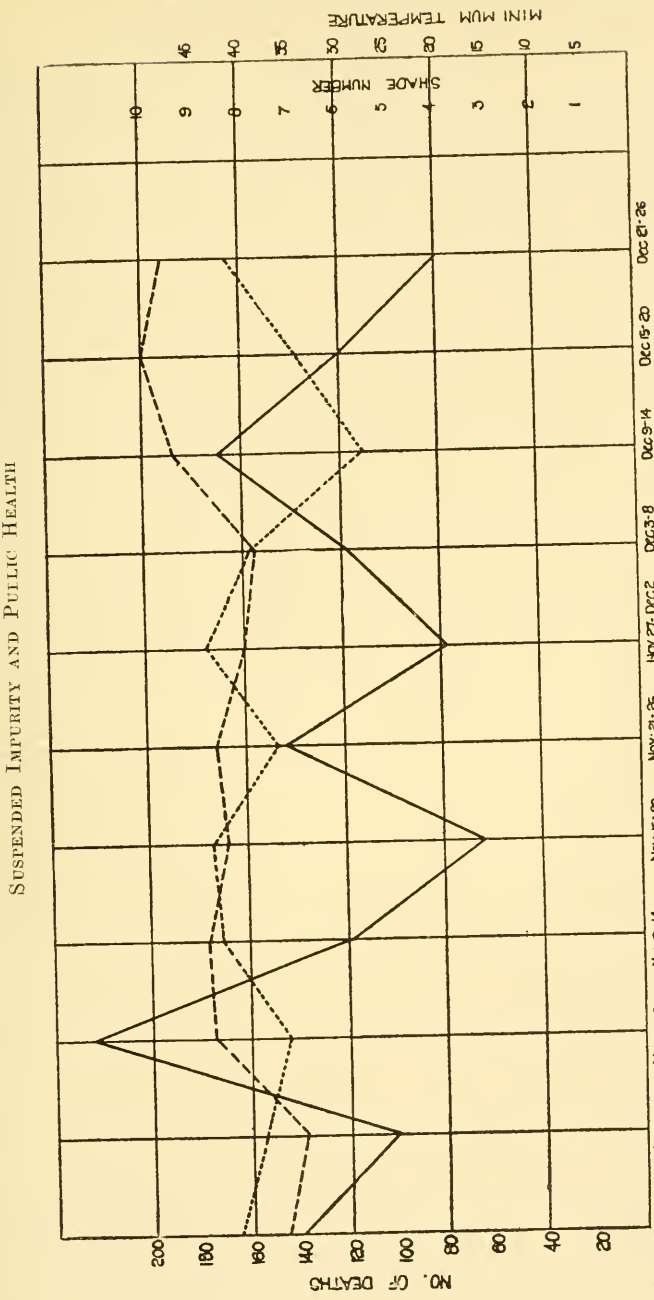

Fig. 13.—The data for suspended impurity, full line; the minimum temperatures, line of dots; and the death rate of London, line of dashes, arranged according to weeks.

There is also the probability that the death rate is not the best means of showing up the effect sought for ; there may be an effect due to acclimatisation by which city dwellers become better able to stand the impure air provided for them than would visitors from parts of the country with purer air. It may be, therefore, that it is in a reduction of general physique that we have to look for the effects of smoky air upon the inhabitants, and, judged from this standpoint, there is not much question as to the relative physique of the country and city dwellers. There is little doubt that the smoky atmosphere which they have to breathe, combined with the loss of sunshine and daylight, is one of the causes of the inferiority of the physique of city dwellers as compared with those of the country.

An investigation is now being made into the relation between the amount of suspended impurity in the air of certain cities and the incidence of bronchial diseases. This is being done by the Ministry of Health in collaboration with the Advisory Committee on Atmospheric Pollution.

Ultra-Violet Light

A highly important investigation has been in hand for some time, by the Department of Applied Physiology of the Medical Research Council, into the loss of ultra-violet rays resulting from the smoke pollution of the air. Through the kindness of Professor Leonard Hill we are enabled to give some of the results of this investigation, and a curve (Fig. 14) exhibiting the data obtained from the experimental observations. It is now well known that the ultra-violet radiation from the sun is of the greatest importance from the point of view of health, and it is hardly going too far to say that these rays are essential to human health.

The method of observation [1] in use is to expose a quartz tube of standard width containing a solution of acetone and methylene blue and, at the end of twenty-four hours or earlier, to note the amount of bleaching of the blue solution by comparing it with a set of standards of blue numbered

[1] *The Times*, December 22nd, 1924.

10 to 3. The standard acetone blue is at the start equal in depth to No. 10. If it is bleached down to tint No. 4, the measurement is recorded as 6 on the scale. Each degree is equivalent in value and represents twice the amount of ultra-violet radiation that suffices to produce a slight flushing of the skin of an average person. The graph is for November for the following stations: Greenwich Observatory; Hampstead, London, N.W.; Harrogate,

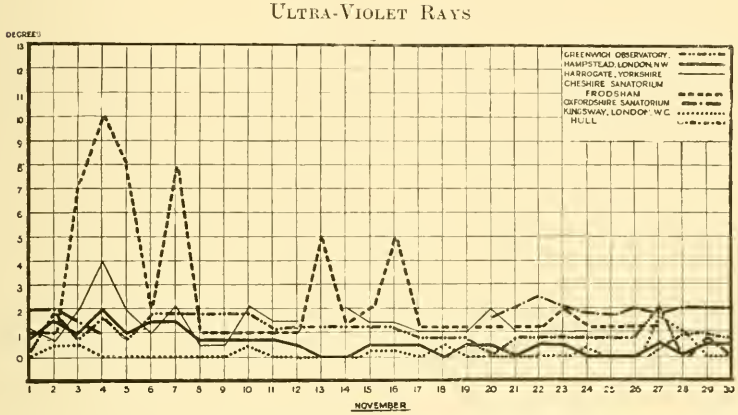

Fig. 14.—Curves showing the total quantity of ultra-violet radiation recorded day by day at the stations named in corner of the diagram, during November, 1924. The fine dotted line shows the results for London (Kingsway).

Yorks.; Cheshire Sanatorium, Frodsham; Oxford Sanatorium, Peppard; Kingsway, London; and Hull.

For our present purpose it will be sufficient to compare the relative amount of ultra-violet at Kingsway, London, the lowest curve, and at Frodsham, on the west coast of Cheshire. It will be observed that there is an enormous deficiency of these life-giving rays in London. It is also remarkable that even at Hampstead, London, the amount of ultra-violet radiation received is much greater than at Kingsway, Hampstead being on the northern heights of the city, while Kingsway is in the valley in the centre. There is no doubt that the smoke pollution of the atmosphere is responsible for the greatest part of this loss.

An interesting article was published in the *Lancet* on August 16th, 1924, by W. T. Russell, communicated by Dr. Brownlie, upon the influence of fog on mortality from respiratory diseases. Statistics were collected for about twenty-seven years for deaths from respiratory diseases of children and adults, and these figures were compared with others showing the amount of fog experienced during those years. Mr. Russell concludes from the analysis of these data :—

1. " That fog itself has no appreciable effect on the respiratory death rate."

2. " That, if the prevalence of fog is associated with a low temperature and frost, the respiratory death rate of adults can be influenced very considerably, although the effect is not evident in the case of children."

In considering the above conclusions, it cannot be too strongly emphasised that the " fog " referred to is not smoke fog, but ordinary white or country fog, and that the data provide no evidence as to the effect of atmospheric pollution as distinct from that of ordinary water fog, so that the problem of the effect of smoke pollution upon the death rate has not been answered by this investigation. There is much confusion in the popular mind between the different types of phenomena ranked under the general name of " fog," and to this confusion must be attributed many misunderstandings of the true nature of the problem.

CHAPTER VI

THE STUDY OF ATMOSPHERIC POLLUTION

Measurement: The Standard Gauge

In 1912 a Committee was formed to develop the investigation of the nature and amount of impurity in the atmosphere, about which at that time there was very little information. Of the Committee the authors were respectively chairman and secretary. After some years of activity, when a considerable number of municipal authorities had associated themselves with the investigation, a grant in aid of the expenses of the central establishment was obtained from Government through the Department of Scientific and Industrial Research. The Committee was thereby brought into association with the Meteorological Office as an Advisory Committee on Atmospheric Pollution, and subsequently attached to the Air Ministry.

Prior to the formation of the Committee a certain number of isolated observations had been made on the amount of impurity in the air of cities. In London, Dr. W. J. Russell [1] measured the suspended matter by filtering air at the rate of 250 cubic feet per hour through glass wool. This was ignited with copper oxide and the carbon and nitrogen estimated. He concluded that during fine weather the suspended impurity amounted to 0·35 mg. per 100 cubic feet of air, in dull weather to 1·03 mg., and during fog to 2·44 mg.

In 1897, Professor J. B. Cohen [2] made a similar measurement in Leeds, near the centre of the town, by filtering air at the rate of 25 to 35 cubic feet per day through a weighed cotton wool plug. The plug was weighed again at intervals. The experiment was made in May and June, 1897, and the

[1] Monthly Weather Report of the Meteorological Office, August, 1885.
[2] *Journal of Society of Chemical Industry*, 1897.

weight of suspended matter was found in one test to be 1·19 mg. per 100 cubic feet of air, and in another 1·20 mg.

With regard to the measurement of deposited impurity, some observations were made in Manchester by Mr. W. Irwin in 1902 [1] by estimating the quantity of impurity contained in snow after it had been exposed for ten days. From this he inferred that there fell in that time about 3·05 tons of soot per square mile, and about 30 tons of soot fell per day on an area of 100 square miles with Manchester as centre.

Mr. F. W. Harris measured the deposit in Glasgow in 1906 by exposing collecting boxes at different parts of the city during four winter months. He calculated that there is a sootfall of 45 tons per day on the area covered by Glasgow, or 896 tons per square mile per year.

In 1910–11, Des Vœux and Owens,[2] in collaboration with the *Lancet* laboratory, obtained figures for the London sootfall indicating a deposit of from 500 to 650 tons per square mile during the year; while at Cheam, in Surrey, eleven miles out of London, the deposit was 195 tons per square mile.

Cohen [3] measured the deposit in Leeds in 1907–08. "The rain was collected by funnels 12 inches in diameter fitting into necks of glass bottles, which were emptied monthly and the contents analysed." This was done at ten stations in and round Leeds for twelve months, from November, 1907, to October, 1908. Deposits were obtained varying from 539 tons per square mile in the industrial district (Leeds Forge) to 25·7 tons per square mile at Roundhay, on the north-east of the city, a residential area.

It will be seen that there is some variation in the figures given above, and it was felt that there was a need for an organised attempt to obtain trustworthy figures by some standardised method as to the degree of smoke pollution in different localities, so that a comparison could be made between town and town, or between town and country; also,

[1] *Journal of Society of Chemical Industry*, 1902, p. 533.
[2] "Sootfall of London," *Lancet*, January 6th, 1912.
[3] Cohen and Ruston: "Smoke: a Study of Town Air." Arnold, 1912.

an estimate could be formed of the effect of efforts made to abate the smoke nuisance.

Such problems as the relation of smoke impurity to health and the decay of buildings could not be tackled effectively without sufficient data upon the smoke content of the atmosphere.

The Advisory Committee on Atmospheric Pollution was originally formed as a result of a meeting of delegates of municipal authorities held in connection with the Smoke Abatement Exhibition in 1912, in London. The original Committee was constituted an Advisory Committee on Atmospheric Pollution in March, 1917.

Ten annual reports have been published, embodying the data collected from about forty different stations. These reports deal fully with the figures for atmospheric pollution.

It was very evident that, for such figures to be of value for comparison, standardised methods of measurement were advisable.

On considering the methods to be adopted, it was decided that a broad distinction should be drawn between impurity deposited automatically from the atmosphere and that which fell so slowly that it might not be deposited within the limits of the inquiry, or perhaps not at all. The two problems thus indicated, that is, the measurement of deposit and the measurement of suspended impurity, were quite distinct, and required the evolution of totally different methods.

It is proposed in this chapter to deal with the measurement of deposited matter alone.

Solid impurities or dust in the atmosphere tend ultimately to settle upon the earth, and the rate of settlement depends upon the size of the dust particles, other things being equal ; in fact, the velocity of settlement will be directly proportional to the square of the diameter of the particle.

From certain points of view the material deposited upon the earth is the most important. As has already been shown, matter deposited on growing plants interferes with their growth, while the sooty deposit upon buildings not only affects their appearance, but is directly injurious to the building stone. On the other hand, the suspended matter

in the air may be of more importance from the point of view of human health, since it is that part of the atmospheric impurities which we breathe into our air passages and lungs, and it is responsible also for the reduction of sunlight in our cities.

Turning now to the question of the deposited impurity, it was decided to measure the quantity which fell upon a given area in a given time, because this appeared a comparatively simple measurement to obtain; whereas to deal with the suspended matter appeared to be much more difficult. The work which the Committee set itself may be defined as follows:—

(*a*) The consideration and specification of standard methods to be adopted, and the carrying out of such researches as might be necessary in this connection.

(*b*) Co-ordination and control of the investigation. It was intended to set up stations in as many parts of the United Kingdom as possible, and the results from such stations would not be of comparative value unless obtained under similar circumstances and conditions. Thus having fixed upon the methods and apparatus to be used, instructions for operation and analysis and a form for reporting the results had to be prepared.

(*c*) The collection of statistics.

(*d*) The compilation and discussion of the information, and the publication of an annual report.

The Measurement of Deposited Impurity

Considering first the method of measuring deposited impurity.

A preliminary investigation on this point had been carried out in 1910 and 1911 at three stations in London and one near Cheam, in Surrey, under the auspices of the *Lancet*.

For this purpose a square open-topped gauge vessel was used, having a catchment area of 4 square feet, and terminating in a narrow tube at the bottom. The first plan tried was to fit at the bottom of this gauge vessel a cylindrical filter packed with glass wool, the idea being that the glass

wool would retain all the deposited matter while permitting the rain water to escape. It was soon found, however, that this method was useless, as the filters were apparently soluble in rain water, and, therefore, instead of gaining weight by the acquisition of deposit, actually lost weight. A further objection to the method was that it could only collect the insoluble portions of the deposit. Anything which was soluble in rain water would be lost.

It was, therefore, decided to abandon this method and collect all the rain water which fell into the open top of the gauge vessel. A year's observations with four gauges were made, commencing February, 1910, and ending February, 1911, and the results were published in the *Lancet* of January 6th, 1912, under the heading "The Sootfall of London."

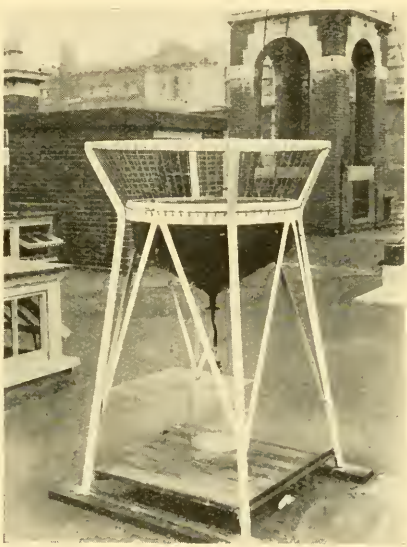

Fig. 15.—The standard gauge.

The gauge vessel used in the above experiments was made from sheet iron with enamel painted on. This was found to be quite suitable for a short period, but the vessels rapidly deteriorated after their year's work. The information obtained, however, was useful in designing the standard gauge as used by the Committee. In this gauge, which is shown in the accompanying diagram (Fig. 15), the vessel is circular in plan, instead of being square, and is composed of cast iron enamelled with a vitreous enamel. Great care was taken in selecting the enamel so as to get one as insoluble as possible. Another little point in connection with this vessel was that the vitreous enamel would not

spread over a sharp corner of metal, but in the process of stoving the surface tension of the melted enamel pulled it away from the corner on each side. Hence all corners had to be rounded in order to get a good protection with enamel. Another difficulty encountered was due to the warping of the gauge vessel in the process of enamelling. It was intended that the catchment area should be 4 square feet exactly, and the upper edges of the vessels were turned in order to give accuracy ; when, however, they were stoved in the process of enamelling all the vessels warped slightly, so that they ceased to be truly circular. It was, therefore, found necessary to measure each vessel separately, and thus to ascertain its catchment area. The latter differed very slightly from 4 square feet in any case, but as it was intended that returns of deposit should be made in the form of metric tons per square kilometre, a factor was worked out for each gauge vessel which would, when multiplied into the deposit in grammes, give tons per square kilometre.

This factor differed slightly for each vessel ; it also served to convert litres of water into millimetres of rainfall. It will be seen from the illustration that the upper surface of the gauge vessel stands 4 feet above the ground level, and the bottles are on a shelf below, to receive the rain water and deposit carried down, sufficient capacity being provided for one month's rain, as it was intended to make analyses once a month. The wire screen shown surrounding the gauge vessel is provided in order to prevent birds from perching on the edge of the vessel, and it has proved quite effective for this purpose.

In the working of this standard gauge certain difficulties were met with. For example, during heavy frosts the bottles sometimes burst, and various methods of protecting them from frost were adopted, the usual one being to wrap them in some non-conducting covering. In exposed positions the lower part of the gauge was boarded in. Again, the vessel was subject to artificial contamination ; for example, boys amused themselves throwing stones and gravel into some of the gauges, and in one of the London gauges we have had an exceptional deposit of insoluble matter due to the dust

Form 4761.
(Formerly Form No. 6100)

No. of Report.....

METEOROLOGICAL OFFICE, AIR MINISTRY, LONDON.

ADVISORY COMMITTEE ON ATMOSPHERIC POLLUTION.

REPORT OF OBSERVATIONS FOR MONTH ENDING.....192.....

Centre..... { Gauge No..... / Factor "F" for gauge.....

Collector.....

Volume of Water Collected.....litres=.....Millimetres of rainfall

Total Solids dissolved.....grammes } dried @ 100° C.
Total Insoluble matter..... }

Total Solids Collected.....grammes=.....tons per sq. Kilometre

	Grammes.	% of Total Solids.	Metric tons per square Kilometre.
COMPOSITION OF UNDISSOLVED MATTER :—			
Soluble in CS_2 (tarry matter).....	.....	= ..... %	.....
Combustible matter insoluble in CS_2	.....	= ..... %	.....
Ash.....	.....	= ..... %	.....
Total undissolved matter....			
COMPOSITION OF DISSOLVED MATTER :—			
Loss on ignition.....	.....	= ..... %	.....
Ash.....	.....	= ..... %	.....
Total dissolved matter....			
Sulphate as SO_3	.....	= ..... %	.....
Chlorine as Cl.	.....	= ..... %	.....
Ammonia as NH_3.....	.....	= ..... %	.....

REMARKS :—

Date..... Signed.....

FIG. 16.—Form for recording results obtained from the standard gauge.

thrown up by bursting bombs from German raiders. In the autumn, leaves occasionally blow into the vessels, and the spores of plants are details also collected.

It was found that the impurity carried down by the rain water was washed into the bottles, but in dry weather matter was also deposited upon the inside surface of the gauge vessel, and this was so adherent as to resist washing off by subsequent rain. It was, therefore, arranged that in changing the bottles each month the inside surface of the gauge vessel should be washed down with a brush or squeegee with some of the water already collected, the washings being added to the water in the bottles.

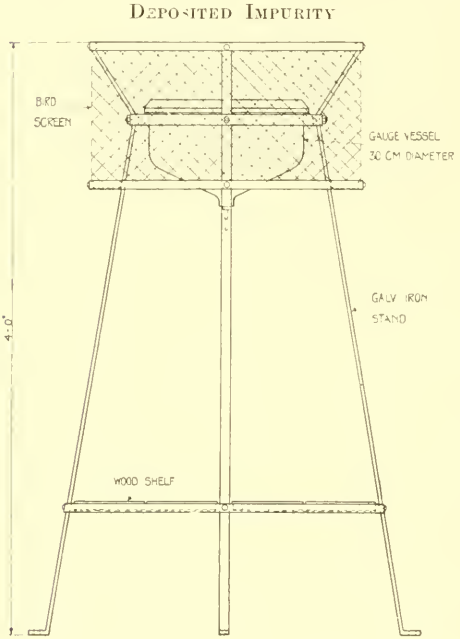

Fig. 17.—The stoneware gauge.

Care was taken in the selection of sites for these gauges so that they would not be subject to any abnormal pollution due to the proximity of smoky chimneys, dust of roads, or other apparent source of pollution. All gauges were placed, where possible, upon the ground level.

A special form, as shown on p. 81 (Fig. 16), was prepared and supplied to the co-operating authorities for making their returns to the Committee, and it will be noted that the analysis of the deposited matter is not intended to be complete, but rather to give only the more important constituents. The amount of deposit is returned on these reports as grammes, percentage of total solids, and metric tons per square kilometre. The choice of the latter unit

was made because chemical laboratories in this country use metric units for scientific investigations. Subsequently it was found that the number of grammes per square dekametre (100 square metres) gave figures which required no decimal point, and had the further advantage of referring to an area which could easily be visualised, since a dekametre is about the width of a street. In spite of these advantages, we are using English tons per square mile in this work in deference to the imagined prejudices of the reader.

It was subsequently found advisable to modify the standard gauge described above. A smaller instrument was designed, in which the gauge vessel itself was formed from stoneware with an acid-proof vitreous enamel. This gauge is illustrated in Fig. 17.

In the following table a list of stations is given for the years 1914–24. The figures in this table are given in tons per square mile. When there is more than one station in the same city, the figure given in the table represents the average of the stations.

A glance at the table shows the great difference in the amount of impurity deposited at different places. It is evident that London is not the worst.

The station for Malvern is in the country, at Malvern Wells, and, therefore, the deposit may be taken as representing the open country. If smoke could be entirely done away with, the deposited impurity in cities should be reduced to something approaching that found at Malvern.

Objection is sometimes raised by local representatives against the publication of the amounts of deposit as likely to prejudice the interest of towns in which large amounts are collected ; but the real result of the publication is to demonstrate that the local authorities are concerned for the purity of the atmosphere and for facing facts, a reputation of which any town may justly be proud.

It must not be assumed that the cities which show the greatest deposits are the worst in the country ; observations are not taken in all cities, and it does not follow that there are not other localities with more smoke pollution than those given in the table.

TABLE I.—LIST OF STATIONS ARRANGED IN ORDER, SHOWING TOTAL IMPURITY DEPOSITED IN SUMMER AND WINTER: MEAN MONTHLY DEPOSIT IN ENGLISH TONS PER SQUARE MILE

SUMMER.		WINTER.	
1914. *April to September.*		1914–15. *October to March.*	
Birmingham—Central	55	Oldham	89
Oldham	53	Birmingham—Central	63
Bolton	51	Bolton	58
Liverpool	48	*Glasgow*	55
Manchester	47	Liverpool	48
Newcastle	35	Paisley	47
Paisley	33	Newcastle	45
London	32	*Manchester*	44
Kingston-upon-Hull	31	Kingston-upon-Hull	38
Sheffield	29	*London*	36
Greenock	23	*Sheffield*	35
York	20	Greenock	31
Exeter	20	York	26
Leith	16	Exeter	25
Malvern	6	Leith	24
		Coatbridge	20
		Malvern	5
1915. *April to September.*		1915–16. *October to March.*	
Oldham	74	Oldham	84
Liverpool	50	*Manchester*	59
Manchester	49	Newcastle	51
Bolton	42	Liverpool	48
Newcastle	35	*Glasgow*	46
London	34	Bolton	45
Birmingham—Aston	33	Leicester	44
Kingston-upon-Hull	32	*London*	41
Leicester	31	Kingston-upon-Hull	36
Greenock	31	Greenock	34
Sheffield	31	Coatbridge	27
Glasgow	30	Leith	25
Coatbridge	24	York	25
Leith	24	Exeter	22
Exeter	20	Malvern	5
York	16		
Malvern	4		

NOTE.—The figures against the names in *italics* are averages for more than one station.

TABLE I.—*continued.*

SUMMER.		WINTER.	
1916. *April to September.*		1916–17. *October to March.*	
Newcastle	53	Newcastle	66
Manchester	52	*Manchester*	48
Glasgow	49	Greenock	43
London	35	Coatbridge	37
Greenock	33	*London*	36
Leicester	30	*Glasgow*	35
Coatbridge	27	Leicester	33
Leith	25	York	23
Exeter	23	Malvern	10
York	21		
Malvern	5		
1917. *April to September.*		1917–18. *October to March.*	
Rochdale	89	Rochdale	90
Newcastle	66	St. Helens	51
St. Helens	51	Coatbridge	43
Coatbridge	41	Newcastle	41
Leicester	39	*Glasgow*	38
London	38	*London*	34
Glasgow	35	Leicester	33
Manchester	35	*Manchester*	28
Malvern	8	Malvern	5
1918. *April to September.*		1918–19. *October to March.*	
Rochdale	87	Rochdale	59
Leicester	51	St. Helens	49
St. Helens	42	Coatbridge	48
Newcastle	41	Newcastle	48
Coatbridge	40	*Glasgow*	37
Manchester	38	*London*	37
London	30	*Manchester*	36
Glasgow	26	*Southport*	17
Southport	17	Malvern	11

NOTE.—The figures against the names in *italics* are averages for more than one station.

TABLE I.—*continued.*

SUMMER.		WINTER.	
1919. *April to September.*		1919–20. *October to March.*	
London	30	St. Helens	42
St. Helens	27	*London*	28
Glasgow	26	*Glasgow*	27
Southport	15	*Southport*	15
Malvern	9	Rothamsted	11
Rothamsted	9	Malvern	7
1920. *April to September.*		1920–21. *October to March.*	
Rochdale	78	Liverpool	45
Newcastle	46	Rochdale	43
Liverpool	41	Newcastle	38
Birmingham	39	Kingston-upon-Hull	33
St. Helens	39	*Birmingham*	28
Kingston-upon-Hull	36	St. Helens	25
Glasgow	29	*London*	23
London	28	*Southport*	12
Southport	18	Rothamsted	11
Rothamsted	10		
Malvern	5		
1921. *April to September.*		1921–22. *October to March.*	
Liverpool	51	Newcastle	44
Newcastle	47	Liverpool	43
Rochdale	45	St. Helens	43
Kingston-upon-Hull	38	Rochdale	42
Glasgow	24	Kingston-upon-Hull	32
London	22	*London*	26
St. Helens	21	*Glasgow*	19
Southport	19	*Southport*	15
Rothamsted	12	Malvern	6
Malvern	6		

NOTE.—The figures against the names in *italics* are averages for more than one station.

TABLE I.—*continued.*

SUMMER.		WINTER.	
1922. *April to September.*		1922–23. *October to March.*	
Rochdale	71	Liverpool	58
Blackburn	50	Rochdale	56
Liverpool	49	Blackburn	37
Newcastle	39	*Birmingham*	33
Birmingham	38	Newcastle	33
Leeds	37	St. Helens	33
Kingston-upon-Hull	34	Kingston-upon-Hull	31
St. Helens	32	*London*	25
London	25	*Leeds*	25
Glasgow	24	*Glasgow*	19
Southport	19	*Southport*	11
Rothamsted	10	Rothamsted	5
1923. *April to September.*		1923–24. *October to March.*	
Rochdale	90	Newcastle	96
Blackburn	65	Liverpool	53
Liverpool	57	Rochdale	51
Newcastle	51	Blackburn	41
St. Helens	43	Kingston-upon-Hull	35
Birmingham	39	*Birmingham*	34
Salford	35	*Salford*	34
Kingston-upon-Hull	32	*Leeds*	29
Glasgow	27	St. Helens	28
London	24	*Glasgow*	26
Kingston-on-Thames	10	*London*	24
Southport	10	Kingston-on-Thames	17
Rothamsted	9	*Southport*	10
		Rothamsted	7

One ton per square mile is equivalent to—
3·5 lb. per acre.
0·39 metric ton per square kilometre.
0·39 gramme per square metre.
39·00 grammes per square dekametre.

NOTE.—The figures against the names in *italics* are averages for more than one station.

In Table I. the figures shown are mean monthly quantities. If it is desired to find the total annual deposit, the mean monthly figure for October to March must be multiplied by

six and added to the summer figure for April to September multiplied by six ; the total thus obtained is the deposit for the year, expressed in tons per square mile.

TABLE II.—MEAN MONTHLY DEPOSIT FOR PERIODS OF SIX MONTHS ENDING MARCH 31ST, IN ENGLISH TONS PER SQUARE MILE

	1915	1916	1917	1918	1919
LONDON. (Average of all stations.)					
Total solids	35·66	40·86	35·99	34·20	36·81
Tar	0·28	0·36	0·38	0·23	0·31
Carbonaceous or sooty matter	5·02	6·50	5·27	4·33	5·53
Sulphates	7·50	7·01	6·60	6·40	7·86
GLASGOW. (Blythswood Square.)					
Total solids	—	46·28	35·23	37·45	40·11
Tar	—	0·79	0·41	0·44	0·49
Carbonaceous or sooty matter	—	6·20	6·27	5·48	7·22
Sulphates	—	11·39	7·06	8·78	8·04

	1920	1921	1922	1923	1924
LONDON. (Average of all stations.)					
Total solids	28·03	23·27	25·57	24·96	24·14
Tar	0·26	0·49	0·31	0·26	0·26
Carbonaceous or sooty matter	4·61	5·78	5·50	4·66	5·02
Sulphates	4·41	2·69	2·79	3·23	3·12
GLASGOW. (Blythswood Square.)					
Total solids	30·18	31·79	—	25·57	30·77
Tar	0·20	0·49	—	0·19	0·49
Carbonaceous or sooty matter	2·82	6·47	—	3·56	4·68
Sulphates	5·42	5·17	—	4·35	1·53

If it is desired to express the deposit in other units, the conversion factors given at the end of Table I. may be used.

Separate figures are given for winter and summer. We should naturally expect a larger amount of smoke in winter, the season for domestic fires, although factory furnaces and cooking fires are in operation during the summer. A marked difference is observable in the table, the summer deposit being usually less than that in the winter. The difference in the quantity of smoke pollution is greater than would appear from the figures shown, since some of the deposited matter is due to dust which rises from the ground, and this is naturally greater during the summer season than during the winter. This point will be brought out when we consider the nature of the deposited matter.

It will be observed that some of the cities show a deposit which varies little from year to year, and in several of them the observations have been discontinued, so that comparison is not possible. During the war a large number of stations suspended observations, but some have recommenced.

To give an idea of the variation from year to year the deposits at two cities, London and Glasgow, are given in Table II., and in this case the deposit has been analysed into tar, carbonaceous or sooty matter, and sulphates.

Referring to Table II., it will be seen that in London since 1916 the monthly deposit has fallen from 40·86 tons per square mile in 1916 to 24·14 tons in 1924. In Glasgow the deposit has fallen from 46·28 tons in 1916 to 30·77 tons in 1924.

This shows a marked improvement in the atmosphere of these two cities, and of the two it is evident that the improvement in London is greater than that in Glasgow, though that is still considerable. This shows that much can be done by municipal authorities to reduce smoke.

The amount of sulphur deposited from the air has also fallen very considerably between the years mentioned in both cities, and, as already pointed out, the sulphur compounds are the most injurious of those produced by burning coal.

Here we digress a little to consider a criticism of efforts to abate smoke that is sometimes made. It is based upon the statement that the abolition of smoke would not reduce

the sulphur emitted into the air during combustion. As one of the methods of reducing smoke is the use of gas for domestic heating and cooking, it must be pointed out that in the manufacture of gas a large proportion of the sulphur in the coal is removed from the gas; the residual amount in town gas is usually between 25 and 35 grains per 100 cubic feet.

Soot absorbs the sulphur products, and the sooty matter therefore acts as a vehicle for concentrating and carrying the sulphur acids or sulphates.

Apart, however, from any theoretical consideration, it is of interest to examine the table given above. From this it will be seen that corresponding with the reduction in total deposit there is also a reduction in sulphates deposited. This shows that a reduction in deposited sulphur products can be brought about by reducing smoke.

Nature of Impurity Deposited

We pass now to a consideration of the nature of the impurity deposited from the air, and for the purpose of illustrating this the following table shows the composition of the deposit at five representative stations.

The stations given are selected on the following basis: Oldham is a typical manufacturing city; Sheffield another manufacturing city of a different type; London is a mixed residential, business and manufacturing city; Manchester manufacturing and residential; Malvern is taken as representing the air of the open country.

In the table the percentage composition of the deposit is shown. Tarry matter, which is derived from smoke, varies from 1·31 per cent. of the total deposit in Sheffield to 0 at Malvern. Carbonaceous matter, which includes the soot from smoke, varies from about 20 per cent. of the deposit at Oldham to 8·25 per cent. of that at Malvern. Insoluble mineral matter, which includes dust blown up from roads and other sources, as well as ash carried up the chimneys in the draught, forms 53 per cent. of the Oldham deposit and 14 per cent. of that at Malvern. The soluble

TABLE III.—COMPOSITION OF DEPOSIT AT FIVE REPRESENTATIVE STATIONS, GIVEN IN ENGLISH TONS PER SQUARE MILE AND AS PERCENTAGES OF TOTAL DEPOSIT

Both are based on Mean Monthly Deposit in a Year

Components of Deposit.	Tarry Matter.		Carbonaceous or Sooty Matter.		Mineral Matter Insoluble in Water.		Combustible or Volatile Matter Soluble in Water.		Mineral Matter Soluble in Water.		Total Solids.		Sulphates as SO_3.		Chlorine as Cl.		Ammonia as NH_3.	
Station.	Tons per Sq. Mile.	Per cent. of Total.	Tons per Sq. Mile.	Per cent. of Total.	Tons per Sq. Mile.	Per cent. of Total.	Tons per Sq. Mile.	Per cent. of Total.	Tons per Sq. Mile.	Per cent. of Total.	Tons per Sq. Mile.	Per cent. of Total.	Tons per Sq. Mile.	Per cent. of Total.	Tons per Sq. Mile.	Per cent. of Total.	Tons per Sq. Mile.	Per cent. of Total.
Oldham, 1915–16.	0·56	0·71	16·39	20·08	41·85	53·20	6·16	7·8	13·81	17·5	78·77	100	6·53	8·3	2·27	2·86	0·46	0·58
Sheffield (Attercliffe), 1914–15.	0·72	1·31	9·61	17·60	23·71	43·50	4·58	8·4	15·93	29·3	54·55	100	7·25	13·3	4·02	7·33	0·20	0·38
London, 1915–16 (average of eight stations).	0·29	0·76	5·89	15·60	13·65	36·20	5·07	13·40	12·89	34·10	37·79	100	5·48	14·5	1·74	4·70	0·26	0·70
Malvern, 1915–16.	—	—	0·38	8·25	0·67	14·30	1·25	26·90	2·33	50·00	4·65	100	1·07	23·00	0·50	10·7	0·04	0·82
Manchester, 1915–16 (average of five stations).	0·13	0·41	4·30	13·57	12·13	38·27	3·38	10·66	11·76	37·09	31·69	100	4·79	15·11	1·31	4·13	0·13	0·41

mineral matter deposited at Oldham is 17 per cent. of the total deposit, while at Malvern it is 50 per cent. Soluble mineral matter includes sulphates, derived from combustion, chlorides, probably derived partly from sea spray, and ammonia. In the last three main columns of the table the sulphates, chlorine, and ammonia are given, and we note that at Malvern sulphates were 23 per cent., chlorine 10·7 per cent., as against sulphates 8·3 per cent. and chlorine 2·86 per cent. at Oldham. There are thus great variations in the composition of the deposit as between different places. The main source of sulphates is the combustion of coal containing sulphur, and attention may be drawn to the fact that sulphates formed 23 per cent. of the total deposit at Malvern in 1915–16, which points clearly to the transport from smoky cities of the impurity which is deposited at Malvern.

Although the figure for sulphates estimated as a percentage of total solids at Malvern is so high, the actual quantity of sulphates is very small compared with that in large cities. For example, the 23 per cent. of total solids at Malvern amounted to a total for the year of 1·07 tons per square mile, while the 8·3 per cent. at Oldham came to 6·53 tons per square mile.

The explanation of the various elements into which the deposit is divided was given in the Second Report of the Advisory Committee on Atmospheric Pollution, and may be reproduced here.

Total Solids.—This heading comprises all the solid matter suspended either by itself or in combination with water in the atmosphere. A portion of it may be considered as a legitimate constituent of the atmosphere, as air, free from dust of one kind or another, can only be expected at extremely high altitudes. A portion of the total solids is soluble in water and is found by the evaporation of the deposited water or an aliquot portion of it. The remainder, being insoluble in water, appears mostly as a sediment in the collecting bottles after standing for some time. A small portion may remain suspended in the water, particularly after agitation.

Undissolved Matter.—The matter freely suspended in air and insoluble in the deposited water has, obviously, the first claim for examination. It consists largely of dust from the ground and carbonaceous smoke from the incomplete combustion of raw fuel. The composition of the dust varies in different districts according to the geological and surface features of the ground. It is different in town and country and depends upon the kind and state of roads and other open spaces. The portion due to mineral dust in the undissolved solids can be approximately gauged by their percentage of "ash" (this value also includes the "ash" contained in soot or smoke) obtainable upon ignition. However, before igniting the undissolved matter, it is treated with carbon bisulphide. The portion soluble in carbon bisulphide is largely composed of tarry matter, which is derived from the oily constituents of coal smoke.

It must be remembered that coal, on being burnt in a grate, is partly carbonised, yielding volatile products similar to those obtained from a gas retort. Unless the fuel bed is so arranged that these products undergo complete combustion, they will issue from the chimney along with the unconsumed sooty carbon. The tarry matter gives, therefore, an indication of the amount and character of the soot contained in the deposits. The amount of fatty extract from vegetable or animal dust, which would be recorded under this heading, is probably negligible.

The "loss on ignition" of the undissolved matter represents largely the carbonaceous matter, such as soot, emitted in the form of smoke. It would also include any organic matter of vegetable or animal origin carried into the air in the form of dust. A further, but relatively small, portion consists of water of constitution from clayey matter, carbon dioxide from limestone, and the like.

Dissolved Matter.—The dissolved matter consists of that portion of the total solids which is readily soluble in water, such as chlorides, sulphates, and other salts. Free acids originally present in the atmosphere, such as sulphur dioxide or sulphuric acid, may react with the basic constituents of

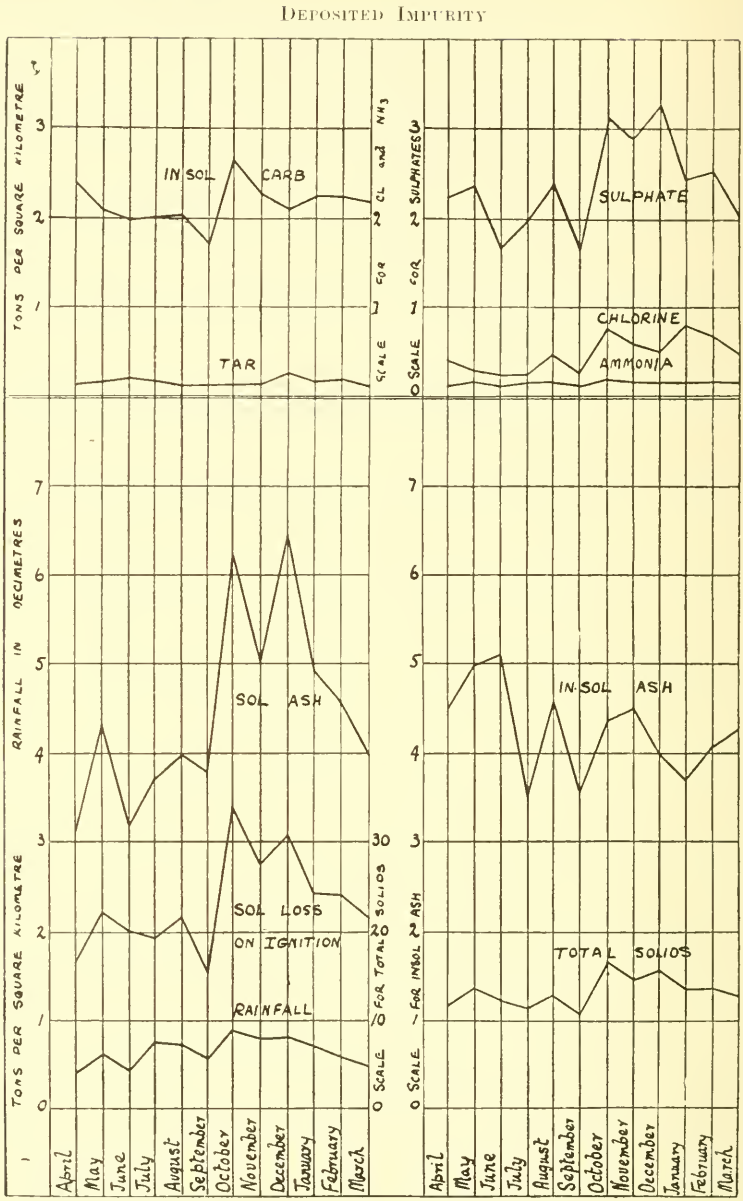

Fig. 18.—Curves showing the relative amounts of rainfall on a decimetre scale and of the several constituents of the deposited impurity in the different months of the year, in scales of tons per square kilometre. Average results for nine large cities in four years.

the undissolved matter and go into solution either in the course of, or after, deposition.

The only analytical treatment to which the dissolved solids are submitted is the estimation by ignition of the total mineral constituents contained in them. The "loss on ignition," being the difference between their original weight and the weight of "ash" obtained, represents partly combustible organic matter and partly water of constitution or volatile products of decomposition, such as carbon dioxide, ammonium salts, sulphuric or sulphurous acid, nitric acid, etc.

Apart from the two items, the sum of which represents the total solids, the separate estimation of a few constituents, already included in the total or in one of the items, is made, as it appears to throw some light upon the character of the various deposits.

Sulphates.—The sulphates present in the liquid portion are estimated and returned in terms of SO_3—*i.e.*, sulphur trioxide or sulphuric anhydride—which represents the acid portion of all sulphates. The basic portion, such as ammonia, soda, lime, alumina, is not included in this figure. This item can be taken to represent the oxides of sulphur derived from the combustion of coal, oil, or gas containing sulphur of any kind.

Chlorides.—The chlorides are returned in terms of Cl, and do not, therefore, include the basic portion, which would probably consist of alkali or magnesia. It is probable that the greater portion of the chlorides is due to wind-borne sea water spray.

Ammonia.—This is returned as free ammonia (NH_3), although it is probably present in most cases in the form of salts, such as sulphate or chloride. It may be derived from the carbonisation of coal in open fires and also from the decomposition or degradation of vegetable or animal nitrogenous matter.

The set of curves shown in Fig. 18 illustrates the distribution of the deposit over the different months of the year. In order to eliminate peculiarities applying to single stations or to particular years, the curves have been prepared from a

group of nine stations and for a period of four years. A study of these curves will illustrate the points referred to. The vertical scales for the different elements of pollution are not the same, so that each must be examined relative to its own scale.

The coal strike which occurred in 1921 provided a remarkable object lesson in the amount of impurity in the air derived from burning coal. The strike commenced on April 1st, and finished on July 4th. In considering the effect upon atmospheric impurities it must be remembered that the strike would not affect the quantity of coal burnt until coal stocks had become reduced. In order to eliminate uncertainty as much as possible, the last month of the coal strike has been considered, that is, June, 1921. The amount of deposit from the air for this month has been compared with that for the same month of the years preceding and following. Since the month of June occurs at a period of year when the amount of wind-blown dust is likely to be large, the carbonaceous deposit, which is composed mainly of soot, has been taken separately from the other figures as the most suitable for comparison with the previous and subsequent years.

The table given below shows the figures mentioned ; they refer only to the London area, and the remarkable reduction during the month of June is well brought out :—

Deposit in Tons per Square Mile in London

June, 1920 .	Total Solids,	29·60.	Carbonaceous Matter (Soot),		6·81
June, 1921 .	,, ,,	14·60.	,, ,,	,,	2·18
June, 1922 .	,, ,,	25·91.	,, ,,	,,	5·32

Thus the total deposit in June, 1921, amounted only to 53 per cent. of the mean of the values for 1920 and 1922, while the deposit of sooty matter in 1921 was only 36 per cent. of the mean of the other two years.

Rainfall and Deposit

The method described for measuring deposit from the air has been criticised on the supposition that the amount of

deposit depended upon the rainfall rather than upon the amount of impurity in the air. An investigation was therefore made to elucidate the relation, if any, between rainfall and the recorded deposit of solid matter. A somewhat curious result was met with. It was found that, while the deposit of insoluble matter from the air showed no relation whatever to the rainfall, the quantity of soluble matter deposited did show some relation. It would appear, therefore, that the effect of rain is to bring down the soluble impurities of the atmosphere, but that it has little effect, if any, in bringing down insoluble matter or soot.

The question was examined by plotting the rainfall against the deposit for different stations, and for a large group of stations taken together. The result is interesting, and may find an explanation on the following basis. It is known that the first step in the formation of rain is the condensation of water vapour in the upper regions of the atmosphere to form small drops, which subsequently grow, under suitable conditions, until they attain sufficient size to fall as rain. It is known that water vapour will not condense in free air without nuclei for the drops. These nuclei may be supplied in a variety of ways, but they do not represent dust in the sense which is ordinarily understood. The most effective nuclei are particles of some hygroscopic salt. Particles of sulphuric anhydride are excessively hygroscopic, and other soluble salts formed from sulphuric acid are more or less hygroscopic. The same may be said of chlorides derived from sea spray ; hence we should expect that, when condensation commences, such hygroscopic nuclei would be selected to form the cores of the drops, the sooty particles taking no part themselves, because not only are they non-hygroscopic, but, owing to their tarry nature, they tend to repel water. Thus we have a selective action by which soluble matter is taken by the rain and the insoluble part left.

It may, therefore, be stated definitely that the deposit of sooty matter from the air is little, if at all, affected by the rainfall.

It may be thought that falling rain drops must pick up the suspended dirt on their way, but their action in this respect is probably negligible. Each drop as it falls displaces the air in front of it, and thus a current of air is formed moving out of the way of the drop; it is doubtless capable of sweeping the fine suspended particles away so that the drop does not strike them. A similar phenomenon is observed in the case of small floating bodies at the bow of a ship; they are pushed aside by the current of displaced water, and thus do not come in contact with the ship.

Settlement of Impurity from the Air

The smoke and other solid matters emitted from chimneys tend to settle to the ground, and would all do so with varying degrees of rapidity, depending upon the size and nature of the particles, if there were no forces operating to prevent it. As already pointed out, the rising of the warm gases from the chimneys gives the smoke an initial upward movement which lifts it into the wind currents and thus permits it to be carried away. Owing to the difference in size and other properties of the smoke particles which are carried up the chimneys, we may expect that a grading will take place in consequence of which the smaller travel a greater distance. Large smuts formed by the aggregation of numbers of smaller particles settle comparatively rapidly, and any one who has been in the immediate neighbourhood of a very smoky chimney is aware of the deposit of such smuts in the vicinity. The draught from a fire or furnace carries up a number of particles of ash, and, while these are mostly irregular in shape, some of them are spherical and solid, while others may be similarly spherical but hollow. The little solid fused balls settle more rapidly through the air than the more irregularly shaped particles. Thus there are forces which tend to modify the composition of the impurity as the distance from its source increases. The smoke from domestic chimneys has already been referred to as containing a larger proportion of tar than that from industrial furnaces; it is also much richer in carbonaceous

matter, as the combustion is more imperfect in domestic fires than in the industrial furnaces. Again, the velocity of the draught in industrial furnaces is much higher than that from domestic fires, with the result that a larger proportion of ash is carried up. The presence, therefore, in deposited matter of high percentages of tar or carbonaceous matter points towards the domestic fire as its source, while the presence of high proportions of ash, with relatively little tar and carbonaceous matter, points towards industrial smoke.

There is one form of industrial furnace which produces a somewhat remarkable type of smoke ; that is the pulverised coal furnace, a form in which finely powdered coal is blown into the combustion chamber of a boiler or other furnace with a suitable quantity of air in the form of a blast. Under these circumstances the powdered coal burns like a gas flame. It is important in such furnaces that the fuel should be completely burnt and the resulting ash have time to cool to the solid form before it strikes the lining of the furnace or the boiler tubes, as it is likely to be fused by the high temperature of the flame. When so fused, it is liable to form a layer of adherent slag or cinder if it strikes any surface while in the molten state.

It will be seen that this condition also favours the production of spherical particles, since the fused ash, while suspended in the blast inside the furnace, assumes the spherical form, and retains this if it solidifies before striking the walls. As a result, it has been found that the ash from such furnaces and the smoke, or rather grit, which is emitted from the chimneys consists to a large extent of such fused spherical particles ; owing to the small size of the particles, the smoke travels a considerable distance.

Sometimes such points are of importance, as, for example, when it is required to know whether the deposit of grit or impurity comes from a plant using pulverised fuel or from ordinary furnaces in the same neighbourhood. These little spherical particles are coloured, sometimes very brilliantly, and under the microscope, many look like rubies or little crystal globes.

Rate of Settlement

The rate of settlement of smoke particles through the air is of great importance, since it governs the distance to which they are carried from their source. While the particles are settling through the air they are being drifted along by the wind, and the distance to which they are drifted depends upon the time required for them to reach the ground, as well as upon the velocity of the wind. While this is, broadly speaking, a fair statement of the case, it is not possible to calculate exactly the distance which smoke will travel on this basis, since it assumes a rate of settlement through moving air which is based upon that in still air and takes no account of the turbulent motion of the air. This, however, should result in a travel of particles to a greater distance than would be calculated as above indicated.

Sir G. G. Stokes has shown that for very small particles settling through air, something below one-tenth of a millimetre in radius, the terminal or critical velocity at which they will settle is governed by the viscosity of the air and can be calculated from a formula which he evolved in which it is assumed that the terminal velocity is reached when the resistance to downward movement becomes equal to the force producing that movement.

If R = radius of particles in centimetres.
S = density of particle,
S_1 = density of the fluid,
η = viscosity of fluid,
g = the acceleration of gravity.

The terminal velocity of a settling particle, assuming it to be spherical, is given by the following expression :—

$$\frac{2}{9}\frac{R^2(S-S_1)g}{\eta} \text{ cm. per sec.}$$

The viscosity of the air at 15° C. in centimetre-gramme-second units is

$$181 \times 10^{-6}.$$

The viscosity of water vapour at the same temperature and corresponding units is

$$97 \times 10^{-6}$$

$g = 981$ cm. per sec.^{2}

If we assume that the particles of smoke have unit density, while the density of the air may be neglected, the above expression becomes

$$V = R^2 \times 12 \times 10^5$$

for particles settling in air, and

$$V = R^2 \times 22{\cdot}5 \times 10^5$$

for particles settling in water vapour.

The two expressions are given, as it appears possible that the variation in the quantity of water vapour present in the air may affect the final velocity of settlement.

What this expression means is that the particles settle through the air at speeds which vary directly with the square of the radius, and thus a particle 1 micron in diameter (1/1,000 mm.), that is, about the size of a smoke particle, will settle at about 0·003 cm. per sec. If particles of this size are shot out of a chimney 100 feet high and the air is absolutely still, they would take from eleven to twelve days to reach the ground. If there is a light wind blowing of, say, ten miles per hour, and these particles settle at the above rate through the wind from 100 feet high, they would travel about 2,800 miles before all had settled to the ground. It is evident, therefore, that there are possibilities of smoke travelling over immense distances, and, as pointed out elsewhere, there is little doubt that it does so travel over the whole extent of the British Isles.

A factor which modifies the rate of settlement of smoke particles is their tendency to aggregate together into clumps under suitable conditions, and such clumps function as particles of larger radii. For example, on January 11th, 1925, during a dense fog at Cheam, in Surrey, smoke particles were settling out of the air at the rate of 80,000 per square centimetre per minute, as counted in an instrument designed for that purpose; they were settling in clumps or aggre-

gates. Settling singly, without aggregation, the rate should be about 19,000 per square centimetre per minute, as their radii averaged about 0·4 micron. Thus the rate of settlement was enormously increased by the aggregation. The latter figure is obtained from an observation with a jet dust-counter made at about the same time, which showed 15,000 to 16,000 particles of solid matter per cubic centimetre. It is to be understood that such a rapid rate of settlement is probably extremely unusual; the air is seldom sufficiently still to enable the particles so to settle, and it is also probable that the aggregation into clumps only occurs under special circumstances. A test of the rate of settlement made in London on January 12th, 1925, during a much heavier smoke fog containing 27,000 particles per cubic centimetre, showed a number settling of only 1,200 per square centimetre per minute.

CHAPTER VII

THE CAPTURE OF FLOATING IMPURITY

The Dust Filter and Automatic Recorder

The impurity suspended in the air calls for a different method of estimation from that which is employed to measure the deposit. Much thought was given to this problem, the aim being to obtain some method which was sufficiently simple for application without the services of a skilled chemist, and of sufficient accuracy to give quantitative results.

A suitable apparatus would also have to fulfil conditions of portability and cheapness, and of speed of observation as well. The last point is of some importance, since the quantity of suspended impurity in cities varies very rapidly throughout the day. Many possible methods were considered and described in a paper read by Dr. Owens before the British Association in 1913.

It is not necessary to go over this part of the ground here. It was ultimately decided that the most satisfactory and practical method of measurement was by filtration, through white filtering paper, of a measured volume of air, estimating the quantity of impurity present by the depth of the shade produced on the filter paper. The instrument for making this determination is simple, but it has been found to give quite a reasonable degree of accuracy in practice. It is curious to note in this connection that many of the methods hitherto regarded with favour for removing suspended impurities were shown to be ineffective; for example, air bubbled through water and subsequently passed through the filter paper left almost as dark a record on the paper as a sample of air taken at the same time without bubbling through the water.

This is not to be wondered at when it is considered that the floating matter in the bubbles need not come in contact with the liquid, and when it does do so there may not be sufficient time for the liquid to wet it. Again, air passed through a pack of glass wool in a glass tube and then through the paper filter showed little reduction in the amount of suspended impurity to be brought about by the glass wool filter. Suspended matter is extremely finely divided and can easily penetrate the comparatively large interstices of the glass wool.

John Tyndall, in a lecture before the Royal Institution in 1870,[1] stated that he bubbled air through liquid acid and solution of potash, also passed it through a tube packed with broken glass and wetted with sulphuric acid, also through a similar tube packed with fragments of marble wetted with strong potash solution ; but in all these cases the suspended impurities passed through and were made visible by a beam of concentrated light in the vessel into which the air was passed.

It will thus be apparent that the complete removal of suspended impurity is a very difficult matter, but in the filter above referred to it is found that the removal is practically complete, since when two filters are placed in tandem, the air being drawn first through one disc, then through the second, no discoloration or deposit is found on the second disc.

The following is a summary of the methods considered, with a short statement of the objections which were felt to apply to most of them :—

1. Air may be filtered through some medium and the amount of the deposit ascertained by weighing.

2. The *number* of nuclei for condensation can be counted by means of Aitken's dust counter.

3. A jet of air of standard size may be caused to strike a glass plate at a fixed distance from the nozzle, and the opacity of the plate measured after a definite time ; or white paper may be used and the discoloration measured.

4. The opacity of a column of air of given length to a standard light may be measured.

[1] " On Dust and Disease, London," *Proc. R. Inst.*, 6, 1870–72, p. 1.

5. The visibility of objects at fixed distances may be noted and compared from time to time.

6. The impurities may be washed out of a known volume of air and subsequently collected for weighing and analysis.

The objections to the first method are that it is slow and laborious and, unless large volumes of air are dealt with, the weights of deposit are so small as to make it unreliable.

The second may give the number of particles, but takes no account of their size, and it is now known that the nuclei of condensation are distinct from dust as usually understood.

The third gives very rough comparative results; in the absence of special precautions which are considered in Chapter VIII., we are not at liberty to assume (*a*) that all the particles strike against the plate or paper, or (*b*) that all striking particles stick.

The fourth and fifth are only very roughly approximate methods, as the opacity of the air is influenced by water fog as well as by dust particles.

As to the sixth method, seeing that the object in view is to remove all the impurities present, the method of washing did not appear to promise a sufficiently complete removal to make it effective. In washing, for example, by bubbling through water only the surfaces of the bubbles would be in contact with the water, and the resulting cleansing of the air incomplete. Similarly, washing by means of a spray or a scrubber apart from incomplete cleansing would introduce serious difficulties in recovering the impurities washed out.

With all these methods it must be kept in mind that the quantity of impurity present in the air is so extremely small and finely divided that special difficulties are introduced.

The apparatus which will now be described was designed to fulfil the following conditions :—

1. Simplicity of method, so that it would be unnecessary to employ a skilled chemist to take observations.

2. Sufficient accuracy to give reliable quantitative results.

3. Portability and cheapness, as the value would be enhanced if the instrument could be widely used and so give a large number of results at different places for comparison.

4. Speed of observation, to meet the changes in the

atmospheric conditions, which alter very rapidly, especially in cities.

5. Permanence of record for reference.

The Apparatus

In the method used a measured volume of air is filtered through a disc of special paper of standard size, and the discoloration of the paper is compared with a prepared scale. The apparatus consists of a pair of graduated aspirating bottles, D and E (Fig. 19), one of which is filled with water and placed on a stand about 5 feet above the other; into this the water is allowed to run through a rubber tube having a clip F, and terminating in the lower bottle in a short length of glass tube, the use of which will be subsequently explained. The filtering apparatus is fixed in a rubber bung in the upper bottle, and consists of a sleeve C bored eccentrically and carrying two screwed plugs, A and B, axially perforated, one screwed in from each end. These plugs meet opposite a slot in the sleeve C, where their ends are faced so as to fit nicely together and grip the filter paper P, which is inserted through the slot. The holes in these plugs are exactly one-eighth of an inch in diameter. The upper plug has a milled head, as shown in Fig. 19, and the lower one

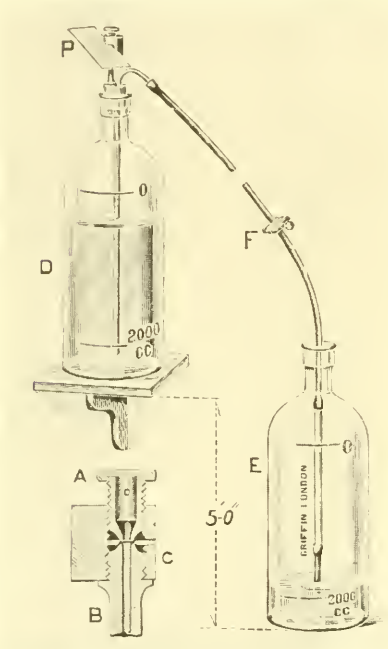

Fig. 19.—Dust-filter for smoky air: single action.

terminates in a projecting nozzle which fits in a hole in the rubber bung. Thus, all air drawn into the upper bottle must enter through a disc of filter paper one-eighth of an inch in diameter.

The standard volume of air used is 2 litres, and marks are put on the bottles to indicate when that amount of water has flowed out ; this gives a measure of the volume of air filtered. As, however, the water flows out under a head of about 5 feet, and the air enters somewhat slowly through the filter, a certain time must be allowed after the water has reached the lower mark and the clip F has been closed before removing the filter paper. From experience it has been found that two to three minutes are required for the air in the upper bottle to reach atmospheric pressure ; but to avoid error, as soon as the required volume of water has passed out and the clip F has been closed to stop further flow, the lower end of the tube is lifted and the glass termination placed beside the upper bottle, in which position it acts as a pressure gauge as soon as clip F is opened, and the water will be seen rising in the glass tube. When it has reached the same level as the water inside the bottle, the filter paper may be removed.

The whole time of taking an observation, from start to finish, is about ten minutes.

The filter paper is held securely by screwing down plug A gently, and can be released, when the record is taken, by slacking back the screw. The record given takes the form of a circular discoloured dot one-eighth of an inch in diameter on the white background of the paper, and the degree of the discoloration is a measure of the amount of impurity present in the air. It is obvious that, to be reliable, the filter paper must catch all the dust particles, and it was only with considerable difficulty that a paper capable of doing this was found. The method of testing the paper was to place two discs of paper in tandem in the same filter and to draw the air through both ; if the first paper showed discoloration and the second remained white, it was considered a proof of the efficiency of the paper as a trap for the suspended matter. It was found that thin smooth-surfaced

filter papers were not satisfactory, as they not only gave a spotty record, but permitted some impurities to pass; the spotty nature of the record was doubtless due to the accumulation of the dust particles near small holes. With thick smooth-surfaced paper the records were uniformly shaded, and no particles could be detected on the second paper.

The record papers are printed in the form of oblong slips, as shown in Fig. 20, the upper row of squares being intended to receive the records. When filled up, the slips can be filed away and kept for future reference.

The Scale

To make a comparison between the records from different places without having to compare the actual records with

RECORD										
VOLUME	2ℓ	2ℓ	2ℓ	2ℓ	2ℓ	2ℓ	2ℓ	2ℓ	2ℓ	2ℓ
SHADE Nº	25	4	5	6	5	4	4	3	3	2
TIME	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm
DATE	9.2.14	9.2.14	9.2.14	9.2.14	9.2.14	9.2.14	9.2.14	9.2.14	9.2.14	9.2.14
PLACE	London	London	London	London	London	London	London	London	London	London
REMARKS	Clear	Haze	Fog	Fog	Fog	Haze	Clearing	Clearing	Clearing	Clear

Fig. 20.—Form of Record Papers.

each other, a scale of shades has been prepared. This scale is made by superimposing layers of a standard wash of lampblack on a white paper. Ten different shades are provided, numbered, 1, 2, 3, 4, 6, 8, 10, 12, 15, and 20, and each number represents so many layers of the standard wash. Thus, the unit shade once fixed, the rest represent multiples of that unit. Since the scale is, therefore, numbered strictly in proportion to the amount of lampblack deposited on each shade, it follows that, when a record is matched with the scale, the shade number represents the amount of impurity deposited in the record, referred to the unit. If we ascertain the value of the unit in terms of the weight of the deposit on the filter paper, we have a ready means of reading directly

the actual weight of impurity present in the air, say, in milligrammes per cubic metre.

In this apparatus it is necessary that the volume of air should be measured with considerable accuracy. It was thought possible that a measure of the amount of impurity might be given by the time required for a certain volume of air to pass through the paper. The rate of aspiration through filter paper is altered as the pores become choked with impurity trapped from the air, and this results in a longer time being required to filter a certain volume of dirty air than if the air were clean. Experiments were made to ascertain the rate of choking thus brought about, and it was found to be quite insufficient to be used as a basis of measurement. For example, 2,000 c.c. of London air was aspirated through clean paper in four minutes, while after fourteen similar volumes had been drawn through, leaving their impurity behind, the fifteenth volume of 2,000 c.c. required five minutes thirty-five seconds to pass; the difference of pressure on each side of the filter was practically constant in both cases.

Calibration

The calibration of the scale of shades was done by Mr. J. G. Clark, F.C.S., and is fully described elsewhere.[1] The general method adopted was to filter through large discs of filter paper a sufficient volume of air to get a deposit that could be weighed. It was thought at first that it would then be a simple matter to compare the degree of discoloration of the filter disc with the scale of shades, and thus to ascertain the value of the unit on the latter. The filter disc used in the standard instrument just described is one-eighth of an inch in diameter, while the diameter of the disc used for calibration by Mr. Clark was $2\frac{1}{2}$ inches, that is, 400 times the area of the filter disc. A curious difficulty was, however, at once met with. The quantity of suspended impurity was so small that even when a sufficient volume of air was drawn through to make the $2\frac{1}{2}$-inch disc quite black, there was not

[1] Second Report, Committee for the Investigation of Atmospheric Pollution.

Fig. 21.—Twin filters and gas meters used in the calibration of filter deposits.

sufficient impurity to weigh with accuracy. This was partly due to difficulties in the weighing connected with the hygroscopic nature of the paper used for the filter, and the disc

had to be very carefully dried before weighing. To get over the difficulty of the small quantity of impurity required to blacken the paper completely, a modification of the method became necessary. The apparatus as ultimately used is shown in Fig. 21.

This consisted of two separate filter-discs, each $2\frac{1}{2}$ inches diameter, through which air was simultaneously drawn from the same place by means of an aspirator electrically driven. The volume of air drawn through each disc was adjusted so that one received approximately ten times as much as the other, the actual amount being ascertained by passing the air through two gas meters. Correction was also made for the reduced pressure of air as it passed the meters, as it was found that the heavy filter had a reduction of pressure behind it of between 5 and 6 feet of water, while the light filter had a reduction of only about 3 inches of water. This difference of pressure was due partly to the necessity for drawing a larger volume of air through the same sized filtering disc, and it was aggravated as the impurity accumulated on the paper. It gave rise to one curious result during the experiment. The large gas meter collapsed under the outside pressure, and had to be specially strengthened.

By means of this double filter it was possible to draw sufficient air through the heavy one to get a weighable quantity of impurity long before the other paper was completely blackened. Through the other filter a sufficient quantity of air was drawn to get a definite shade on the scale; thus, the ratio between the volumes drawn through the two discs being known, the scale number could be read from the lighter disc while the quantity of impurity represented on that disc was obtained by weighing that on the heavier one, allowance being made for the smaller volume drawn through the lighter filter.

Many other difficulties were encountered, but these were ultimately overcome, and it was made possible in this way to give a numerical value in milligrammes per cubic metre to the unit of shade used on the scale. This value was found to be 0·32 mg. for the unit shade. For example, when a

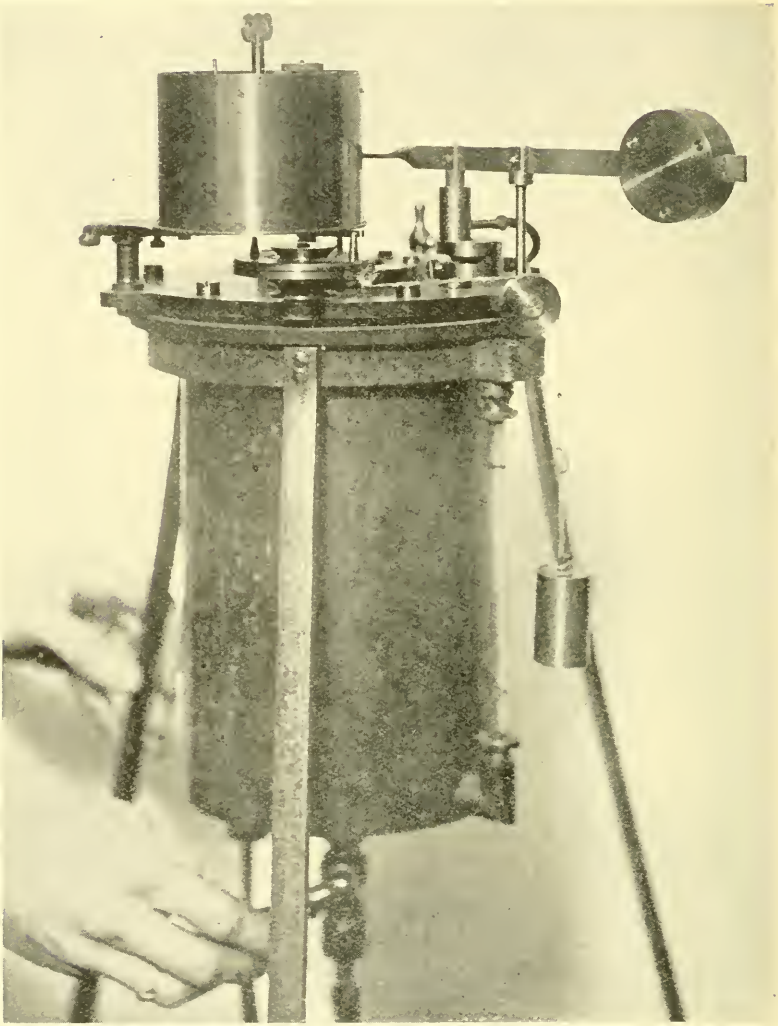

Fig. 22.—Photograph of standard automatic recording filter on its tripod stand.

record taken on the standard filter matched the shade numbered 6 on the scale, the quantity of impurity present in the air could be taken as equal to $6 \times 0{\cdot}32$ mg. per cubic metre.

An Automatic Recording Filter

By means of the standard instrument it was possible to take a record of the suspended impurity in a city at any time, but since personal attention was necessary, it appeared advisable to attempt an instrument which would be automatic in its action, since the number of records is likely to be small when separate personal attention is required for each.

An instrument, shown in Figs. 22 and 23, was, therefore, devised which operated on exactly the same prineiple as the single-record filter already described. By an automatic arrangement two litres of air could be filtered at regular intervals through filter discs one-eighth of an inch in diameter. Thus the same volume of air was used and the disc had the same diameter, so that the scale of shades, the calibration of which has just been described, was applicable to either instrument.

Description of the Automatic Instrument

The instrument consists of a main vessel into which water is admitted through an inlet at the bottom. A siphon is fixed inside the vessel, which allows the water to rise and fall between two fixed levels, thus alternately driving air out of the vessel and drawing it in through an air-inlet-plug.

The plug is hollow and slides up and down in an air-inlet sleeve which has a horizontal slot in which the edge of the filter-paper-dise is placed. When air is drawn in, the air-inlet-plug is automatieally brought down on the filter-paper-disc so as to make an airtight joint, and all air drawn into the main vessel must pass through the filter paper ; the impurities are left behind on it, and a discoloured disc or spot is made. When the siphon has finished working and the water rises again, the pressure on the air-inlet-plug is automatically released, a counterbalance weight lifts it and the disc is free to move.

The air-inlet-plug is made to press on the filter paper in the following way. Inside the main vessel is a bell with its

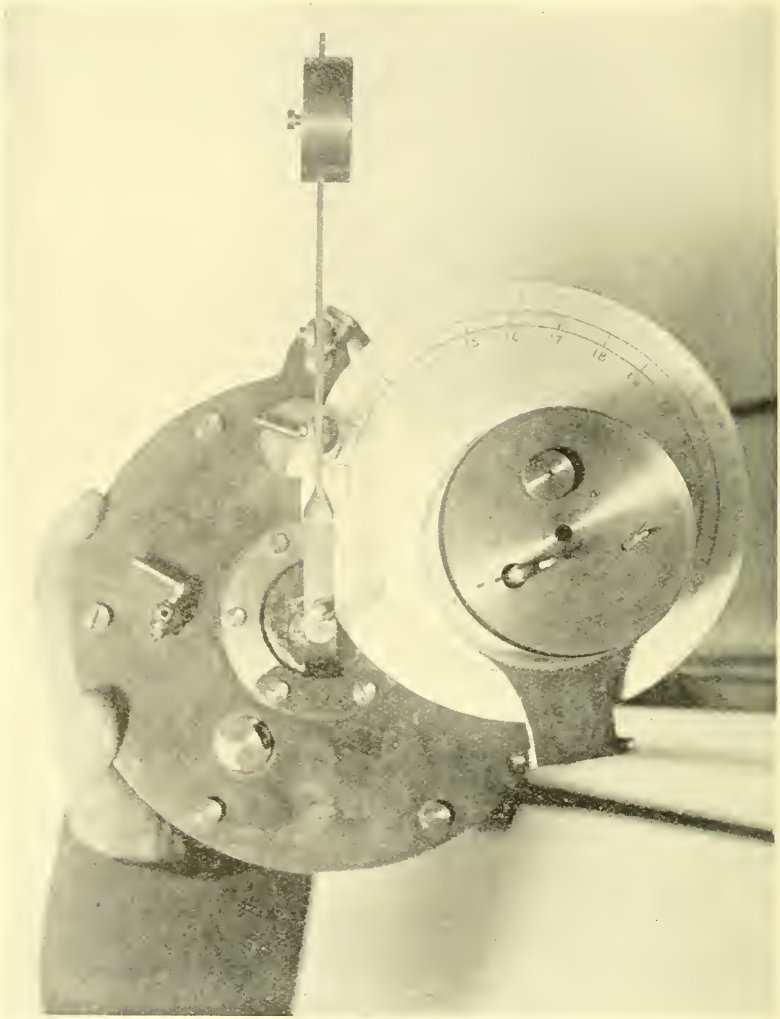

Fig. 23.—Photograph of top of the automatic recording filter, showing a filter paper disc in position with records of impurity, in the form of grey spots, round its edge.

mouth downwards ; this is mounted on a central rod which has at its bottom the valve sleeve. When the water is at the higher level, the bell is full of water, and when the siphon

acts and the water level falls, it cannot fall inside the bell, because the air cannot enter. The weight of water inside the bell pulls it down and the central rod with it, closing the water valve, pulling down the control arm, and thus forcing the air inlet plug down on the filter paper. Then, since air can only enter through the filter paper, the pressure in the main vessel falls as the siphon draws the water out; there is then a pressure of air on the top of a flexible diaphragm which is attached to and also presses down the central rod. When the level has fallen sufficiently, air can enter the bell, and the water falls out, but the diaphragm keeps the plug pressed on to the filter paper.

The water level continues to fall till the siphon breaks and the air in the main vessel returns to atmospheric pressure; then the counterbalance weight lifts the central rod and the air-inlet-plug; it also opens the water valve by lifting the water valve sleeve, which admits water, and the level again rises. The air in the main vessel is now free to pass out through the air-inlet sleeve. The bell has a small float-valve, which lets out the air as the water rises and allows the bell to fill with water; the float-valve, however, will not allow air to enter the bell when the water falls.

After each record has been taken the filter-paper-disc moves through a small angle and the next record is made at a different place. In order that the disc may move in this way, it is mounted on a turntable revolving on a central pivot and operated by a cord passing over a pulley with a weight attached. The turntable is controlled by a clock, which has a boss with an arm on it engaging one of the studs on the turntable; this arm makes one revolution in twenty-four hours. The weight keeps the stud on the turntable pressing against the arm on the clock boss, except when a record is being taken; during that time the disc is held by the air-inlet-plug, and the turntable cannot turn; the arm on the clock boss then moves on until the air-inlet-plug is lifted, and the turntable is again free to move, and its stud can follow up the arm. Thus each record is placed automatically on the filter-paper-disc opposite the time when it was taken.

In this way two litres of air are drawn through the filter-paper-disc at regular intervals, leaving records of the impurities present in the air.

A record disc with its ring of records round the outer

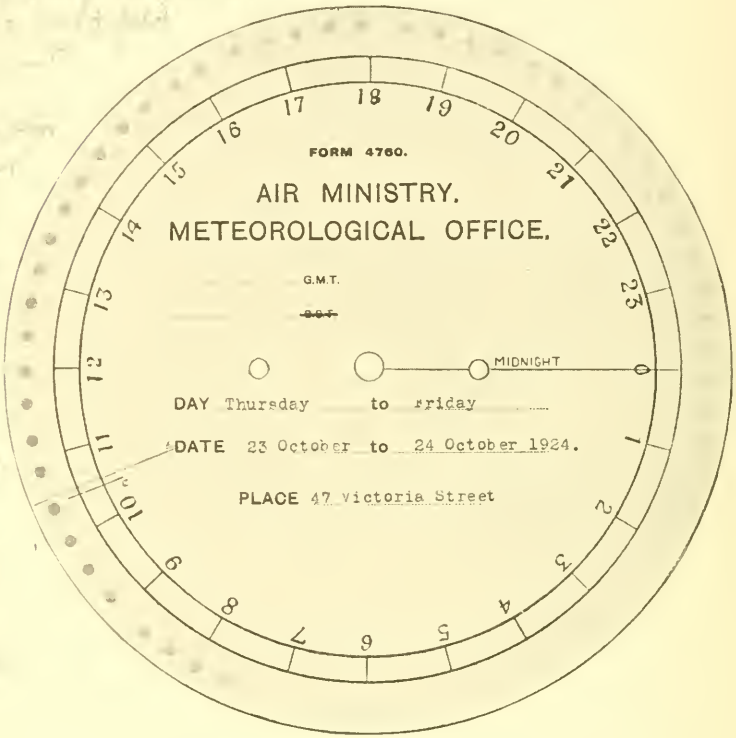

Fig. 24.—The filter-paper disc upon which the impurity records are obtained. The round spots on the edge are the records, the intensity of shade of which measures quantity of impurity.

edge in the form of $\frac{1}{8}$-inch spots of different degrees of darkness is shown in Fig. 24.

Having obtained a number of records from such an instrument over a long period, say, one year, the numerical values, either in shade numbers or milligrammes per cubic metre, are tabulated. After tabulation, the days are divided into three groups—ordinary weekdays, Saturdays, and Sundays. The conditions governing smoke production

remain much the same between Monday and Friday, whereas on Saturdays factories usually work for half a day, while on Sundays they are mostly shut down. From the tables thus formed for a large number of days averages are prepared and curves plotted for different places showing the average distribution of impurity over the twenty-four hours for each of the three groups. A study of the curves often points to the chief sources, and brings out the relation between smoke pollution and human activities.

Analysis of the Records

In many cities where large quantities of smoke are produced thick smoke hazes are not unusual; these do not arise from abnormal smoke production at the time, but from failure of the natural processes by which the smoke is normally removed. As shown in Chapter II. the failures usually occur during anti-cyclonic weather with very light, indefinite winds and an inversion of the temperature gradient, which prevents the escape upwards of the smoke.

In plotting curves obtained from the automatic recorder it is, therefore, found advisable further to subdivide the days into two groups :—

(1) Those in which the smoke haze was at some time very thick in consequence of some abnormal atmospheric conditions; these are designated "Days of much smoke haze," and referred to in what follows as "Z-days"; and

(2) Those in which the smoke haze was not at any time abnormally thick; designated "Days of little smoke haze" or "ordinary days."

This division is necessarily arbitrary. The limit dividing the two was fixed at days having a maximum impurity at any time as great as or greater than Shade 4, which is equivalent to 1·28 mg. per cubic metre.

The division adopted is, therefore, into days symbolised by—

(1) "Z" or days of much smoke haze; and

(2) Days of little smoke haze (not ranking as "Z").

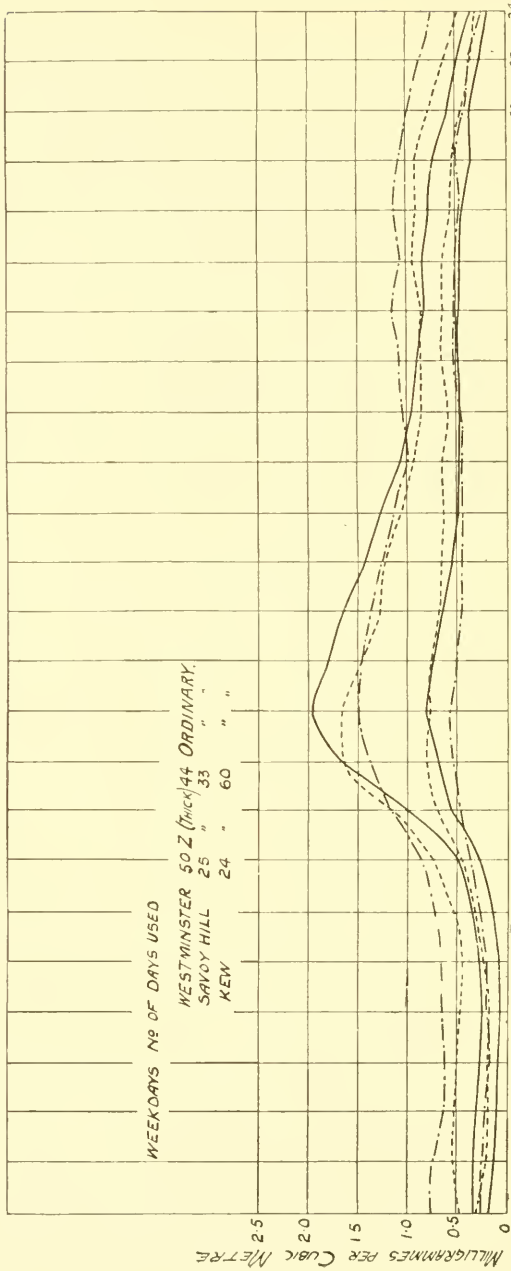
MEASURES OF SUSPENDED IMPURITY : LONDON
WEEKDAYS Nº OF DAYS USED
WESTMINSTER 502 (THICK) 44 ORDINARY
SAVOY HILL 25 " 33 " "
KEW 24 " 60 " "
MILLIGRAMMES PER CUBIC METRE
0 0.5 1.0 1.5 2.0 2.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
TIME G M T

FIG. 25.—Curves showing the average variation from hour to hour of suspended impurity at three London stations in the winter half-year 1921–22.

The three upper curves are for "Z-days" (thick smoke haze), the three lower for ordinary days with no thick haze. The full lines refer to Westminster, the dotted lines to Savoy Hill, and the dot and dash lines to Richmond (Kew Observatory).

It is to be understood that variations in thickness or density of the smoke haze from day to day are usually determined more by atmospheric conditions than by changes in the rate of smoke production.

It will be of interest now to compare a few of these typical curves for different cities. It is evident that the distribution and quantity of impurity present in the air must depend upon the times and quantities of smoke emission. Thus the records of industrial cities and residential cities should be examined for considerable differences. Similarly, the nature of the industry carried on must influence the result.

Curves are shown for London, as a mixed residential and manufacturing city, Fig. 25, Rochdale, Fig. 26, Glasgow, Fig. 27, Blackburn, Fig. 28, and Stoke-on-Trent, Fig. 29, as representing various industrial types.

London.—The London curves of impurity are for Westminster and Savoy Hill, and for Kew Observatory, which is situated at Richmond, about eight miles to the west of the centre of the city.

Only the curve for weekdays is shown, as this illustrates the distribution sufficiently well.

Referring to Fig. 25, the impurity is seen to be at its lowest between midnight and 6 a.m., after which it rises rapidly to a maximum between 9 and 10 a.m., then falls steadily until about 4 o'clock in the afternoon, when there is a tendency to rise slightly to a second, but lower, maximum ; at about 10 p.m. it falls away rapidly until about midnight again. This is quite typical of the London distribution. The Sunday curves are similar, but the maximum is not reached in the forenoon until an hour or two later. There is no doubt that the rise between 6 a.m. and 7 a.m. starts from the lighting up of fires, which make the greatest quantity of smoke soon after lighting. When fires are well established, the smoke is less ; therefore we find the quantity of impurity falling off in the afternoon, while the habit of afternoon tea is probably responsible for the rise about 4 or 5 p.m. The average weekday maximum in winter is about 2 mg. per cubic metre in Westminster, 1·7 at Savoy Hill, and 1·5 at Richmond for "Z-days" ; while for other days

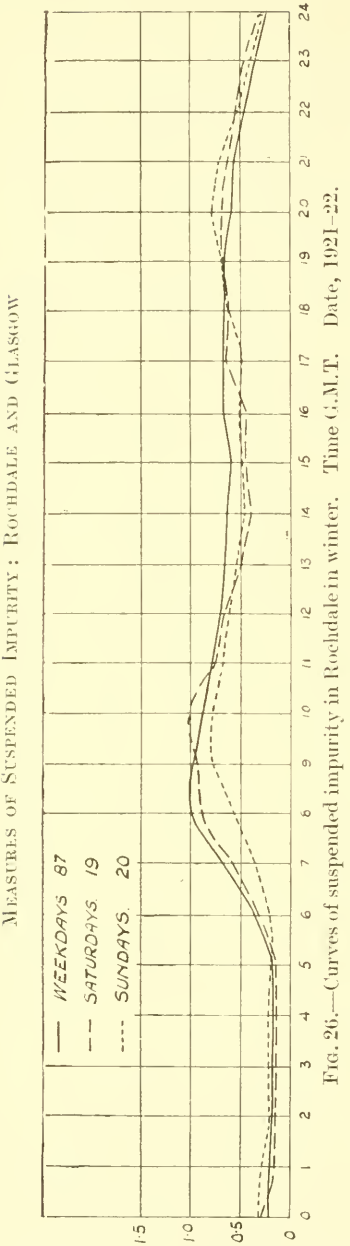
MEASURES OF SUSPENDED IMPURITY: ROCHDALE AND GLASGOW
WEEKDAYS 87
SATURDAYS 19
SUNDAYS 20
MILLIGRAMMES PER CUBIC METRE.
0
0·5
1·0
1·5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

FIG. 26.—Curves of suspended impurity in Rochdale in winter. Time G.M.T. Date, 1921–22.

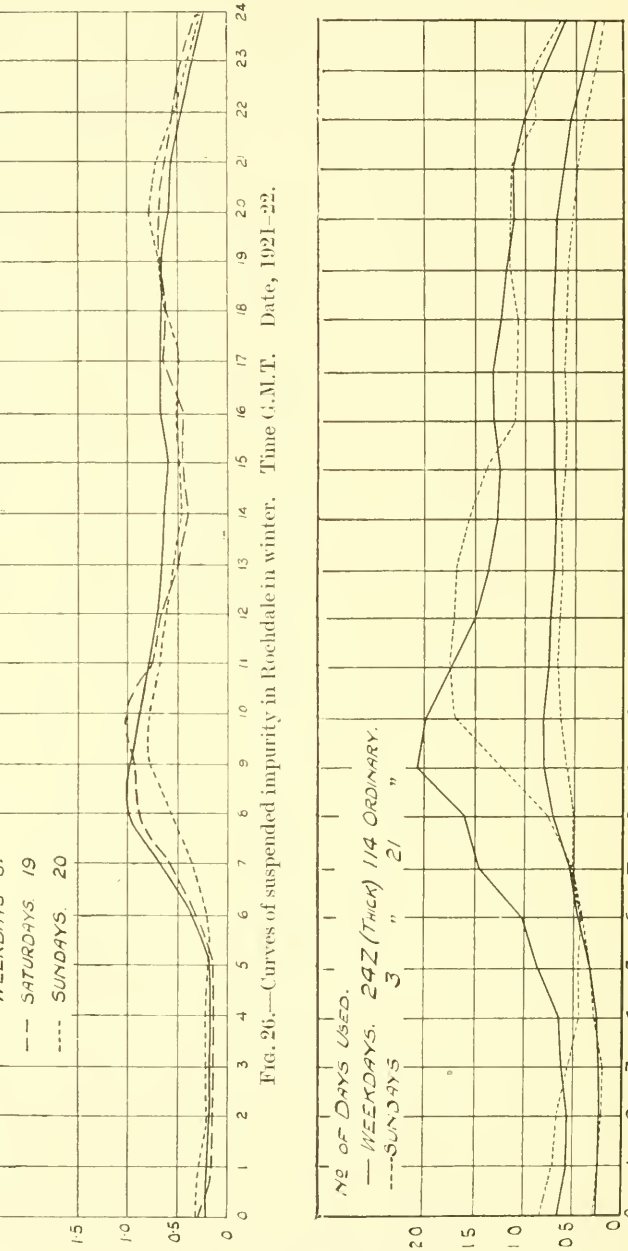
No OF DAYS USED.
— WEEKDAYS. 242 (THICK) 114 ORDINARY.
---SUNDAYS 3 " 21 "
MILLIGRAMMES PER CUBIC METRE.
0
0·5
1·0
1·5
2·0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

FIG. 27.—Curves of suspended impurity in Glasgow Central. The two upper curves are for "Z-days" (thick smoke haze), the two lower for days with no special haze. Time G.M.T.

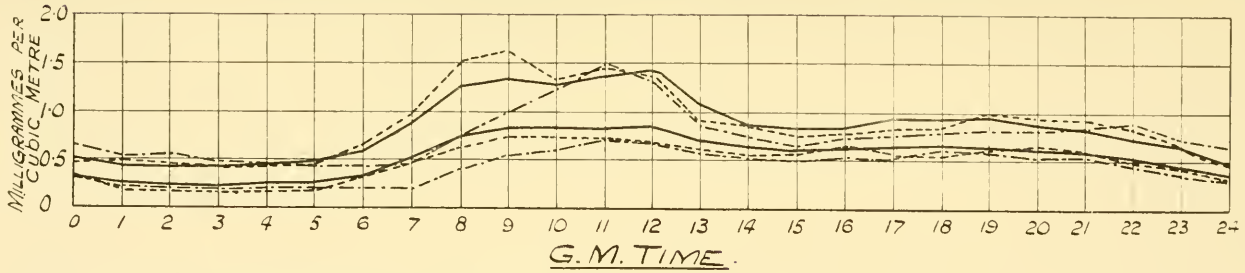

Fig. 28.—Curves of suspended impurity in Blackburn, in winter. The upper three curves are for "Z-days" (thick smoke haze), the lower three for ordinary days without abnormal haze.

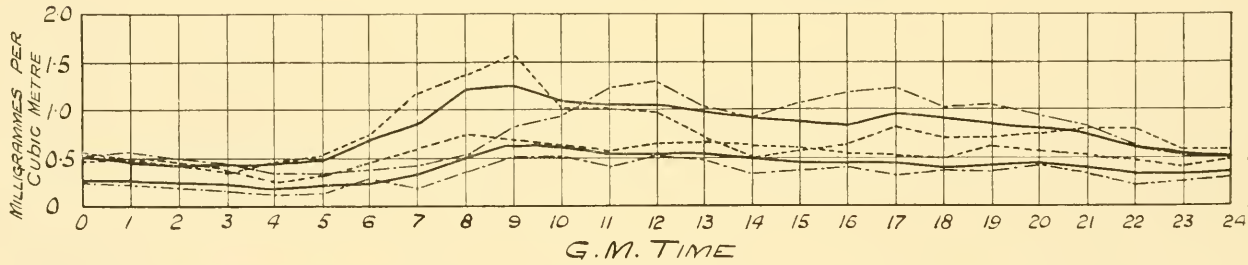

Fig. 29.—Curves of suspended impurity in Stoke-on-Trent. The upper three curves are for "Z-days" (thick smoke haze), the lower three for days without much smoke haze.

In both figures the full lines represent ordinary week-days, the dotted lines, Saturdays, and the dot-and-dash lines, Sundays.

in Westminster and Savoy Hill the average maximum is about 0·8, and that of Richmond about 0·6 mg. per cubic metre. In the summer the quantity is reduced greatly, the maximum for Westminster being under 0·5 mg. per cubic metre.

Rochdale.—In Fig. 26 the average for the winter impurity for each hour of winter days is plotted for Rochdale, and the curve illustrates the similarity in the distribution with that of London. No separation of the "Z-days" from others has been made.

Glasgow.—In Fig. 27 the curve for Glasgow Cross, an industrial district, is given for the winter 1922–23. The distribution over the twenty-four hours is very similar to that in London, except that the falling off in the afternoons of ordinary days is not so well marked, the impurity being maintained at a moderately high level until 8 or 9 p.m. A lag of one hour in the time of the Sunday maximum is very well marked. Saturdays have not been separated from other weekdays here.

In all of these curves a large number of days have been included in the average so as to get a curve fairly representative of the general distribution.

Blackburn.—Curves for Blackburn are shown, as they exhibit some departure from the types already described. These are prepared from records of 269 days of the year 1923–24, 136 being winter days; seventy-two of them rank as "Z," in the sense already defined.

Referring to the curves in Fig. 28, the hourly distribution is broadly similar to that found in other cities, such as Glasgow and London. There is the same rapid increase to a maximum of impurity in the forenoon. There is then an indication of a gradual fall, followed by a subsequent rise to a second maximum late in the afternoon, but less pronounced than that of the morning.

The summer curve, not shown, indicates a uniformly lower impurity than the winter one, and the curves themselves are somewhat smoother, indicating steadier conditions. The distribution, however, has some important peculiarities of its own. For example, the rapid rise of impurity in the

morning commences in the summer about 4 a.m., and reaches its maximum on weekdays and Saturdays at 7 a.m. ; while on Sundays the maximum is not reached until 10 a.m. Thus it would seem that the people of Blackburn are early risers on weekdays, but take a long spell on Sunday mornings. Again, in the weekday and Saturday curves for both summer and winter there is a second maximum between ten and twelve in the forenoon. This is particularly well marked in the winter curves (Fig. 28), where the second weekday maximum occurs at twelve o'clock on " Z-days " as well as on ordinary days. It is higher than the first maximum, which occurs at 8 a.m. In the case both of " Z-days " and ordinary weekdays, the second maximum is higher than the first, and there is a four-hour interval between them. It would seem, therefore, that in Blackburn there are two main sources of smoke, which make their maxima at different times. We get a clue to the position by examining the Sunday curves, which show no evidence of a double maximum in the forenoon. One is therefore inclined to conclude that the first maximum is due to industrial or factory furnaces, and the second to domestic fires. In support of this is the fact that, while in the winter the second maximum is higher than the first for weekdays, in the summer the first is higher than the second. This fits in well with the suggestion that the second maximum is due to domestic smoke.

Another feature which is noticeable in the Blackburn curves is that the minimum impurity is not found until well after midnight. The same feature has been noticed in other cities.

The Sunday curves fall in all cases below those for weekdays or Saturdays indicating a greater purity of the air on Sundays due to the suspension of the work of factories. It is somewhat remarkable, however, that the curves for weekdays, Saturdays, and Sundays lie very close together after the second maximum in the forenoon has been passed ; the greatest difference in all cases is in the forenoon. This is particularly well marked in the case of " Z-days " in winter.

The relation between the total smoke on Sundays and on weekdays is 2,000 to 3,077 ; it is based on the ordinary

winter days not ranking as "Z," and if the Sunday smoke be assumed to be domestic, while on weekdays there is domestic smoke plus factory smoke, the ratio of factory smoke to domestic smoke becomes 1 : 1·85.

Stoke-on-Trent.—Stoke-on-Trent differs from the other cities in the nature of the industry carried on, which is mainly pottery ; hence it is to be expected that the records would show marked peculiarities (Fig. 29).

From Stoke-on-Trent there are records for a total of 222 days. Included in the records are 126 winter days, eighty-two of which rank as "Z." Of the winter days recorded 65 per cent. had thick smoke haze ; hence Stoke-on-Trent appears, roughly speaking, to suffer from thick smoke haze on two days out of every three. This is perhaps not to be wondered at, as it is very difficult to prevent smoke in the pottery industry.

Turning now to the curves in Figs. 25 to 29, there is a definite rise in each of the curves starting between 4 a.m. and 5 a.m. In each city for which curves are shown the minimum amount of impurity is at about 3 a.m., while between midnight and about 6 a.m. the quantity does not rise much above the minimum referred to. This is, therefore, the part of the twenty-four hours which has the purest air.

In Stoke the impurity begins to increase about 4 a.m. on weekdays, and about 5 a.m. on Sundays. On summer weekdays and Saturdays a maximum is reached between 7 a.m. and 8 a.m., while in the winter on weekdays and Saturdays the maximum is somewhat later, between 8 and 9 a.m. On Sundays in the winter the maximum is delayed till about midday.

In both summer and winter the impurity is maintained at a high level during the whole afternoon, with remarkable oscillations, and maxima at intervals during the whole afternoon. The impurity both in winter and summer does not decrease to any marked extent until about 10 p.m., and, as already mentioned, has its lowest value about 3 a.m.

Again, it is noticeable that the amount of impurity on ordinary winter Sundays is not markedly less than on week-

days, the ratio on Sundays and weekdays being 2,022 to 2,398. It is evident that there are conditions here which make it impossible to apply the method already used for ascertaining the relation between factory and domestic smoke, as the method assumes a cessation of factory smoke on Sundays. The general inference one would draw from the curves for Stoke is that the sources of smoke obey no general rule as to starting and stopping. This is what might be expected with pottery kilns, the firing of which would not follow any strictly defined time-table, as in the case of furnaces which are lighted daily. The emission of smoke from kilns does not cease on Sundays, nor is there any regular diurnal or hourly variation.

The curves show that there is definitely less smoke in the summer than in the winter. This is doubtless due to the reduction in domestic smoke in the warmer season.

A remarkable feature of all the Stoke curves for both summer and winter is that in every case the Saturday forenoon maximum is the highest. This might result from firing kilns on Friday night or Saturday morning; on inquiry such a custom was found to exist.

Fluctuations within the Week

With the aid of these records the incidence of atmospheric impurities on the different days of the week can be studied, and, as already hinted, it is found that there is a definite difference observable in the curves.

In the accompanying tables, A and B, for six stations, the total number of each of the days of the week available is given, that is, the numbers of Mondays, Tuesdays, etc., for which there are records available; also the number of such days which rank as "Z," as defined above, and finally a figure showing the number "Z-days," as a percentage of the number of observations.

The results of this table have been plotted in Fig. 30, which brings out graphically the incidence of thick smoke haze.

It is evident that there is a general tendency in practically all stations to a minimum of "Z-days" towards the end of the

TABLE SHOWING THE FREQUENCY OF THICK SMOKE HAZE (Z) IN VARIOUS LOCALITIES ON THE DIFFERENT DAYS OF THE WEEK BY THE NUMBER OF "Z-DAYS" OBSERVED, AND THEIR PERCENTAGE RELATION TO THE NUMBERS OF DAYS OF OBSERVATION

A. *Number of Days of Observation and Number noted as "Z-days"*

		Mon.	Tues.	Wed.	Thur.	Fri.	Sat.	Sun.
Kew Observatory, Richmond.	Days of observation	20	14	16	21	18	21	21
	"Z-days" . .	3	1	2	4	3	1	3
Meteorological Office, South Kensington.	Days of observation	14	15	15	12	17	15	12
	"Z-days" . .	7	8	8	5	9	5	5
Victoria Street, London	Days of observation	17	19	14	18	21	14	15
	"Z-days" . .	9	13	12	14	10	3	5
Westminster Bridge	Days of observation	18	18	19	20	19	19	19
	"Z-days" . .	9	9	10	8	8	5	1
Blackburn . .	Days of observation	19	19	20	20	19	19	19
	"Z-days" . .	11	11	13	8	11	9	7
Stoke-on-Trent .	Days of observation	19	18	17	17	18	18	19
	"Z-days" . .	16	14	12	12	12	9	7

B. *Number of "Z-days" as Percentage of the Number of Days of Observation*

	Mon.	Tues.	Wed.	Thur.	Fri.	Sat.	Sun.
Richmond	15	7	12·5	19	17	5	14
South Kensington	50	53	53	42	53	33	42
Victoria Street	53	69	86	78	48	21	33
Westminster Bridge	50	50	53	40	42	26	5
Blackburn	58	58	65	40	58	47	37
Stoke-on-Trent	84	78	71	71	67	50	37

week, and a maximum near the beginning. An exception to this rule is at Richmond (Kew Observatory), which shows a slight maximum on Thursdays; in fact, the days of thick haze are scattered comparatively uniformly over the week at Richmond. In Victoria Street, Westminster, there is a maximum number of "Z-days" on Wednesdays, with a minimum on Saturdays. At the Meteorological Office, South Kensington, there is a maximum on Tuesdays, Wednesdays and Fridays, and a minimum on Saturdays. Westminster

FIG. 30.—Curves showing the relative incidence of smoke haze on the different days of the week at six stations.

Bridge shows a maximum on Wednesdays, but its minimum is on Sundays, the second lowest being shown on Saturdays.

Stoke-on-Trent shows a maximum on Mondays and a minimum on Sundays, there being a practically steady fall during the week from Monday to the following Sunday. Blackburn has its maximum number of days with thick smoke haze on Wednesdays, and its minimum on Sundays.

The Coal Strike of 1921

Very interesting records were obtained in London during

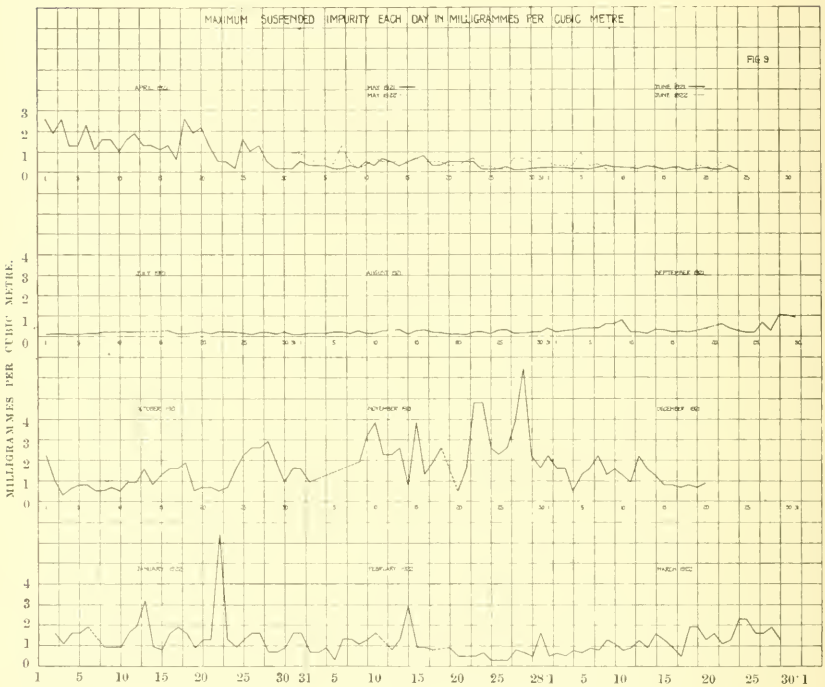
MAXIMUM SUSPENDED IMPURITY EACH DAY IN MILLIGRAMMES PER CUBIC METRE
FIG 9
MILLIGRAMMES PER CUBIC METRE.
1 5 10 15 20 25 30 31 5 10 15 20 25 28 1 5 10 15 20 25 30 1

FIG. 31.—Daily maximum value of impurity in London, April 1st, 1921, to March 31st, 1922, in full line, with the corresponding values in May and June, 1922, in dotted line.

the great coal strike in England, which began on April 1st and terminated on July 4th, 1921.[1]

To bring out the effect of the strike, a curve has been plotted (Fig. 31) showing the maximum impurity for each day during the year, and this curve indicates the remarkably

[1] See also p. 96.

low level reached during May, June, and July. During the month of April there was a steady reduction of impurity until the end, when a fairly low figure was reached, which was maintained throughout the whole period of the strike.

To make a comparison with another summer the figures for the months of May and June, 1922, have been plotted, together with those for the same months of 1921.

Much attention was attracted by the extraordinary clearness of the atmosphere during this period, and although it is normally a period during which the domestic heating fires are not in operation, the reduction of impurity was obviously greater than could be explained by this cause. Reports were published in the newspapers of objects being visible from distances whence they had never been seen before.

Relation of Domestic to Factory Smoke

As a rule it is not necessary to make a special communicating pipe to the open air when taking records with the recorder, as it has been found that the quantity of suspended matter inside a room which is normally ventilated shows no appreciable difference from that outside. In special cases, however, this may not be true, as when there is any abnormal production of dust in a room. The suspended particles are so very small that they appear to follow the air currents without much deposition, and to behave in this respect almost as if the impurity were gaseous.

One of the instruments installed at the Meteorological Office, South Kensington, in the summer of 1924 showed a curious maximum of pollution about 5 p.m. in the afternoon, or a little later. This gave rise to some comment, as there was apparently no special reason to account for it. It was found, however, that this maximum occurred regularly at the time when the cleaners were busy sweeping the floor of the laboratory. The floor was swept one day at 1 p.m., with the result that the maximum appeared on the record at 1 p.m.

By means of the records obtained from the automatic filter, as already indicated, we may examine the relation

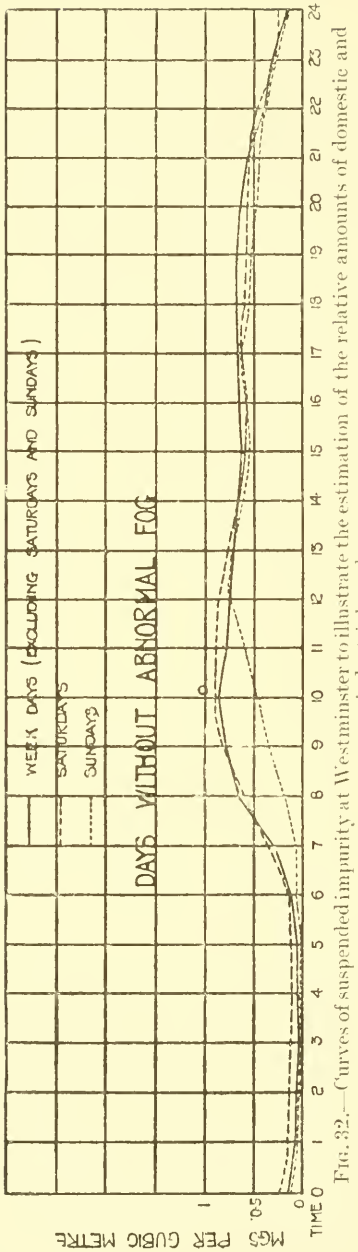
WEEK DAYS (EXCLUDING SATURDAYS AND SUNDAYS)
SATURDAYS
SUNDAYS
DAYS WITHOUT ABNORMAL FOG
MGS PER CUBIC METRE
TIME
0
1
0·5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Fig. 32.—Curves of suspended impurity at Westminster to illustrate the estimation of the relative amounts of domestic and industrial smoke.

between the amount of smoke pollution due to domestic fires and that derived from industrial furnaces.

Let us consider the elementary case of a uniform stream of air, into which smoke is emitted at one point, while records of suspended impurity are continuously taken from another point down-stream. In such a case, as long as other conditions remain constant, any variation in the quantity of smoke emitted will give, a little later, a corresponding variation in the quantity of impurity recorded. Under such conditions the records of suspended impurity are also records of the rate of smoke emission. If now we take a sufficient number of normal winter days, without conditions which cause smoke haze or a banking up of impurities, and the average of such days is plotted, as in Fig. 32, we may regard the curves as showing relative smoke production. Further, since rate of smoke production multiplied by time gives total smoke produced in some unit, the areas enclosed between the curves and the

base line are proportional to total smoke produced in twenty-four hours.

As on weekdays we have both domestic and factory fires in operation, while on Sundays we have domestic fires only, the area enclosed by the curve for Sundays in Fig. 32, deducted from that for weekdays gives in some unit the smoke produced by factories on weekdays. If we call the area of the weekday curve "W," and that of the Sunday curve "S," the ratio of domestic to factory smoke in the air of Westminster, as obtained in this way, is approximately equal to $\frac{S}{W - S}$. Of course, this is only a rough approximation, as certain industrial furnaces are working on Sundays, and also certain fires which would rank as domestic, such as office fires, are not in operation on Sunday.

The curves in Fig. 32 give a mean of forty-six weekdays and eleven Sundays, and the ratio of factory to domestic smoke obtained in the way described above from these curves is as 1 to 2·25.

The records from the instrument at the Meteorological Office, South Kensington, were treated in the same way, and the ratio obtained from them came out as 1 to 2·15. Thus it appears that, in the west of London, the domestic fire is responsible for something over two-thirds of the total smoke.

These figures are obtained from the records of October to March, and therefore apply to the winter period only.

It is not suggested that this ratio holds good for other cities, as it must depend on the relative number of factories and domestic fires. In a manufacturing city the ratio would be very different from that of a residential city.

CHAPTER VIII

NUMBERS AND KINDS OF THE POLLUTING PARTICLES

The Jet Dust Counter

It will be realised from what has been said already that the automatic recorder or filter depends for its results upon the black discoloration of white filter paper by the captured impurity, and is suited for use only when the impurity is known to be black. Specially coloured filter paper could, of course, be used for a particular type of impurity, but, broadly speaking, the automatic recorder is intended to deal with the smoke of cities. For the examination of the finely divided suspended impurity, some other means is required which is not restricted in its application by the colour of the particles. Experiments were therefore made by Dr. Owens to find a suitable method, and ultimately an instrument was evolved known as the "jet dust counter," which fulfilled the conditions laid down.

This instrument depends for its operation upon a well-known physical phenomenon. When air which contains dust and a sufficient amount of water in the form of vapour has its pressure suddenly reduced, there is a fall of temperature and a condensation of moisture into water-drops. Some uncertainty is felt as to the exact process by which the particles of dust, in the sense which the word implies in relation to atmospheric pollution, become possessed of their share of water, whether they are themselves the originators of condensation, or whether condensation first takes place on hygroscopic nuclei and the condensed water captures the dust. The difference is not of importance at the moment. If the particles thus enveloped in water-drops be brought into contact with a glass surface, they will adhere; the

water can be evaporated and the particles examined. This result is brought about in the apparatus referred to by causing a very fine ribbon-shaped jet of air to strike a cover-glass placed about a millimetre from the opening which forms the jet; the air, before entering the jet, passes through a damping chamber; the loss of pressure which gives velocity to the jet causes a condensation of moisture at the moment of striking the cover-glass; the dust particles with the condensed water stick to the glass, the moisture is subsequently evaporated as the velocity falls off, and the pressure and temperature again rise. For efficient action it is found desirable that the velocity of the air in the jet should be very high; it is therefore made as nearly as possible equal to the velocity of sound.

The evolution of this instrument involved a large amount of investigation. In the early stages experiments were made with a round jet formed from a piece of drawn and bent glass tubing; the jet was fixed inside a small bottle in such a way that a microscope slip could be held within about a millimetre of the orifice, so that when air was drawn from the bottle and entered through the jet, it impinged upon the glass slip, and some of the dust was found to adhere. This apparatus was tried in order to find what was the order of its efficiency and whether this could be improved, if necessary, by smearing the glass with sticky substances. It was found that the dust adhering to the glass was not a very high percentage of the total, probably of the order of 20 to 30 per cent., and this was not improved by smearing the glass with sticky liquid, such as thick paraffin and the like. It was also found that sticky liquids on the slides were blown away from the point of impact of the jet. In any case, the amount of dust caught was not sensibly increased by their use. This experience raised the question of the cause of the dust sticking to the glass, since apparently no improvement was gained by smearing the glass with a sticky substance; it is probable that some other process operated to cause adhesion.

In order to investigate this question, a form of jet was designed which could be placed upon the stage of a microscope and the process observed while the jet of air was

striking the glass surface. In this case a small brass holder was made, the floor of which was formed of a sheet of mica, and over this, at a height of about a millimetre, a circular cover-glass could be placed and held in position by a screwed sleeve. By a side connection to the holder air could be drawn from the cell enclosed between the cover-glass and the mica floor ; in the mica floor a circular hole about 0·1 mm. in diameter was made. Thus, when the cell was placed on the stage of the microscope and light reflected upwards through it, the objective could be focussed upon the cover-glass immediately over the hole in the floor. And when air was drawn out of the cell by means of a small air pump, the dust particles could be seen impinging against the lower surface of the cover-glass. By watching this process carefully it was observed that many of the dust particles were surrounded by small drops of liquid. In this way it was discovered that, under suitable conditions, dust particles could be loaded with water in the air just before impinging upon the cover-glass. It is obvious that, in order to cause the jet, air has to be drawn from the cell, and that implies a reduction of pressure in the cell. Again, if the velocity of the jet is high, there is a material fall of static pressure in the jet itself, owing to loss of velocity head. Hence the conditions are suitable for condensation. If, therefore, the air before entering the jet is saturated with moisture, or so near saturation that the reduction of pressure brought about as above will result in super-saturation, some water will be condensed and be deposited with the dust. It will in most cases evaporate and leave the particles adhering to the glass surface when the velocity of the air falls off after impact with the glass.

This form of jet was found to be extremely sensitive, so that a small fraction of a cubic centimetre of air passed through the jet produced a rain of dust particles too numerous to count, except with very pure air. Also, the record was of very small dimensions, and, therefore, extremely difficult to find, except in the way above referred to—that is, by focussing first upon the orifice forming the jet and then racking up and focussing upon the cover-glass immediately

above the orifice. Again, the small quantity of air required to give a record in this form of apparatus appeared likely to result in error, as a sample taken might not be strictly representative. It was, therefore, decided to modify the apparatus in some way so as to get over these difficulties. In the new instrument the orifice for producing the jet consisted of a slot of about one-tenth of a millimetre in width and of any suitable length up to one centimetre, depending upon the size of the cover-glass used. This form was free from the above-mentioned objections, as the quantity of air which could be drawn through the jet without obtaining too many dust particles for counting could be greatly increased; further, there was now no difficulty in finding the record on the cover-glass, as the record itself was of linear form, extending across the glass, the jet being of ribbon shape.

The Efficiency of the Jet

At this stage an attempt was made to measure the efficiency of the apparatus by means of a double jet, the second one taking the air which had passed through the first one. An apparatus was constructed on the lines of that already described, so that the operation could be watched under the microscope. In this the lower cell had a slot in its floor, the jet from which struck its roof, which roof again formed the floor of the upper cell and contained another slot, so that the air, having impinged upon its lower surface, passed through the second slot and impinged upon the roof of the upper cell. The construction of an apparatus with slots of this type was found easy in comparison with the making of an apparatus with a round orifice of very small and fixed diameter. The slots were made in this apparatus by cementing the two halves of a cover-glass to a metallic ring, the slot being formed between the two straight edges, which were ground and polished. The arrangement of the slots was such that they were on opposite sides of the centre of the apparatus. If the first jet stopped all the dust, there would obviously be no dust carried through with the second jet, and none would be found upon the roof of the second cell. Tested in this way, it was found that a varying percentage

of the total dust was trapped, sometimes 100 per cent., and at other times perhaps 50 per cent.

This method of testing the efficiency is not really satisfactory, as it is possible that particles which escape the first cell may escape the second. Again, as the adhesion of the particles is due to water, the first cell may remove a sufficient quantity of the water from the air to reduce the efficiency of the second cell. From the peculiar variations in the quantity of dust trapped it appeared probable that irregularity might be due partly to variations in the moisture contents of the air, as well as to changes in the dust contents. Therefore a damping chamber was devised through which the air had to pass before entering the jet. This chamber had its walls lined with damp blotting paper, and was so arranged that the air would have to spend some time in the chamber before entering the jet. The use of the damping chamber was found to make the records consistent, and from recent results with the double cell it appears probable that all the dust in the air is trapped, or, at least, that the amount escaping is negligible.

The Working Instrument

After these preliminary experiments, an instrument was designed for general use, and this is illustrated in Fig. 33.

The apparatus may be constructed of brass, and is usually nickel-plated ; it consists of a sleeve B, open at the top and bottom and screwed internally for the reception of a screwed plug K. The plug is perforated by a central hole for admitting air to a narrow slot A, formed diametrically across the hole by means of two semicircular metallic plates, held in position by a ring R, attached to the plug K by screws. The upper surface of this ring is recessed to form a bed for a microscope cover-glass, and the ring is of such a thickness that, when the cover-glass is placed in position in its recess, it forms the roof of a cell about a millimetre high. The floor of this cell consists of the afore-mentioned metallic plates with the slot between them, approximately one-tenth of a millimetre in width. The centre of the ring R is turned out to a suitable diameter, which in practice is found to lie between 2 mm. and 10 mm. ; the diameter of the central

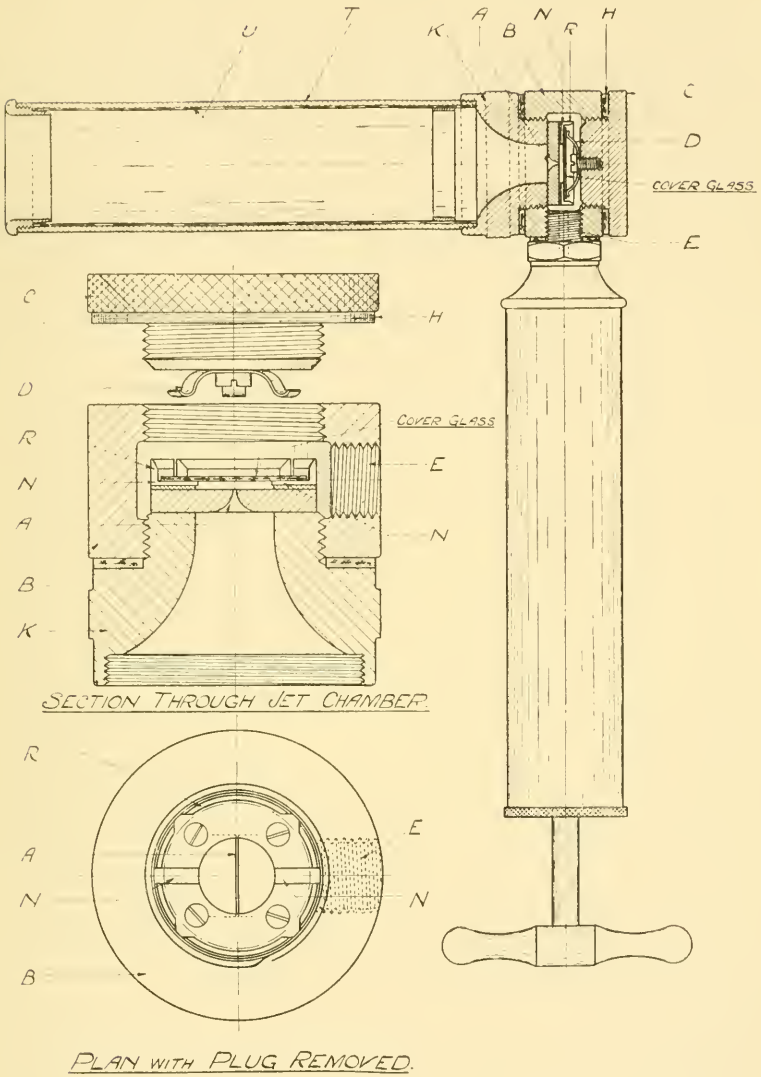

FIG. 33.—The construction of the jet-dust counter. U—E, the instrument with its parts assembled. C, D—H, the plug which secures the cover-glass and closes the expansion cell (full size). R, K—E, N, a section through the head of the instrument with the plug removed (full size), R, B—E, N, plan of the cell ready for the cover-glass showing the slot which forms the jet (full size).

opening in the ring also determines the size of the cell included between the cover-glass and the metal plates. The length of the slot A is also determined by the diameter of the opening in the afore-mentioned ring, or of the central opening of the plug K. Into the upper opening of the sleeve B fits a screwed plug C, to the inner end of which is fixed a spring with three claws, by means of which the cover-glass is held firmly upon its bed when the plug C is screwed home. A washer H, of leather or other suitable material, forms an air-tight joint between the plug C and the sleeve B. The sleeve B has an annular recess formed in its inner wall between the inner end of the plugs C and K, and communicating with this recess is a connection E for attachment to an air pump. Channels N are formed on the upper surface of the ring R, which receives the cover-glass, as shown in Fig. 33, so that when air is drawn from the space between the plugs C and K, by means of an air pump attached to E, a jet of air is caused to enter the slot A and impinge upon the cover-glass, escaping to the annular space in B and the connection to the pump E by means of these channels.

An approach tube or damping chamber T is provided, which may be screwed to the plug K as shown, and which is lined with absorbent material, such as blotting paper, held in position by a spring clip. During use this absorbent lining is wet with water, and its function is to supply moisture to the air before it enters the jet A. The capacity of this damping chamber is two or three times that of the air-pump attached to E. In operation an ordinary hand air pump is fixed to the connection E. The pump is of known capacity. It is found in practice that a capacity of 50 c.c. is suitable, but it may be varied if desired.

The Process of an Observation

In taking a record of the dust, the procedure is as follows :—

The air pump having been attached to the connection E, a few strokes of the pump are made, so that the damping chamber T is filled with the air to be tested. The plug C is then removed rapidly and a carefully cleaned cover-glass

placed in position upon the ring R, after which the plug C is replaced rapidly and screwed home. The pump is then operated so as to draw one or more volumes of air through the jet A, a suitable interval being allowed to elapse between each stroke of the pump, so that the air in the damping chamber T may absorb water from the damp lining. The jet of air, entering through A and striking the cover-glass, deposits its dust thereon. The plug C is then removed, after which the cover-glass may be dropped out on to the hand by inverting the instrument. The cover-glass may then be mounted for microscopic examination of the particles.

Method of Counting the Dust Particles

The record obtained is a band of dust particles of uniform scatter across the cover-glass. A specimen record, taken during a dense fog in London, is shown in Fig. 34 as a bold line of uniform width crossing the central portion of the cover-glass, which is attached to a glass microscope slide by a sticky ring, designed for that purpose, and clearly shown in the figure. By a sufficient number of strokes of the pump a record can generally be made dense enough to be easily seen with the naked eye, but would then be too dense to be counted under the microscope. Nevertheless, with an adjustment of the number of strokes to the occasion, the records lend themselves to a simple method of counting. A micrometer eyepiece, ruled in squares either 0·5 mm. or 1 mm. wide, may be used; the number of particles in a strip of the width of one of these squares, extending completely across the record, can be easily ascertained. The number of strips contained in the record may be found once for all by calculation or by direct counting under the microscope (Fig. 35). Since the volume of air drawn through

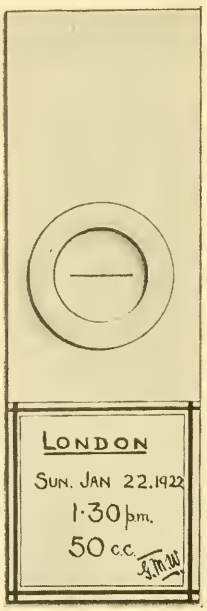

FIG. 34.—A dense record, mounted.

the cell is known, a factor can be worked out for each jet by which the count of one strip across the record must be multiplied in order to give the number of particles per cubic centimetre of air. The counting is done under a microscope with $\frac{1}{12}$-inch oil-immersion objective. In the apparatus, which has been in regular use for some time, the factor is 13·3, assuming 50 c.c. of air are drawn through. Thus, if

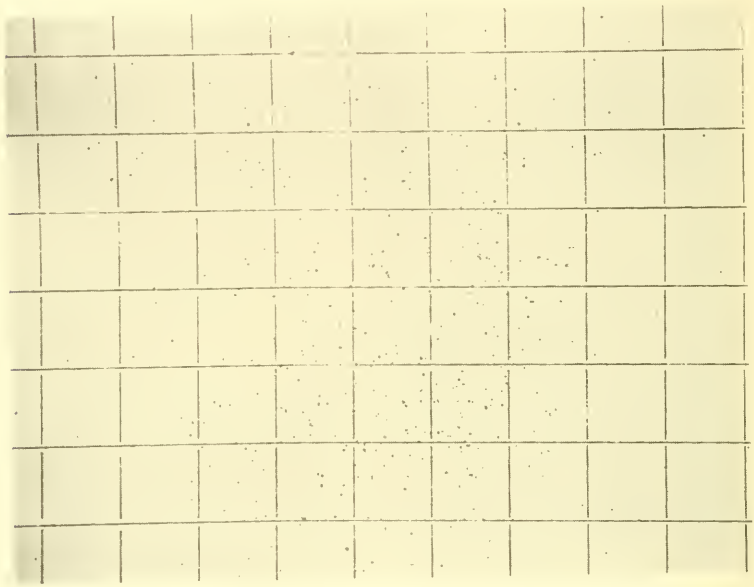

Fig. 35.—Dust record photographed with square ruled micrometer eye-piece in position, to show method of counting. The particles are of London smoke magnified 250 diameters.

N be the number of particles in one transverse strip across the record, 13·3 N will be the number of particles per cubic centimetre. Although the condensed water is an important factor in causing the dust to adhere to the cover-glass, it evaporates immediately the cover-glass is removed, as it is very small in quantity, and, therefore, the record itself, after removal, contains no water drops, and thus no error arises from the fact that drops condense round particles other than dust. Again, the method does not depend in any sense upon

the colour of the particles ; hence it is applicable to dust of all kinds.

In addition to a count of the number per cubic centimetre of air, the size of the particles and their shape can be easily ascertained by direct observation under the microscope ; also some information may be obtained as to their nature by examination in polarised light and other methods, to be described later.

Results of Observation with the Jet Dust Counter

Dust Counts

As illustrating some of the results obtained from records by this instrument, a few typical dust counts are given below. During the dense fog on Sunday, January 22nd, 1922 (Fig. 34), a record of 50 c.c. taken gave 21,750 particles per cubic centimetre. A large proportion of these particles were 1·7 micron in diameter, while the average diameter was about 0·85 micron. The number of large-sized particles found during this fog was quite unusual ; such particles are usually very few. During the fog on October 26th, 1921, in London, the number of particles per cubic centimetre was 20,800, the average size of the particles was 0·85 micron, and the maximum was 1·7 micron. There were a considerable number of spherical particles up to 0·85 micron in diameter. For dealing with comparatively pure air the volume drawn through the jet may be increased ; for example, in samples taken on the coast of Norfolk during August, 1921, it was found necessary sometimes to draw 1,000 cc. in order to obtain a suitable record. During a slight haze in dry, sunny weather, about 100 to 200 particles per cubic centimetre were found, the size ranging from about 0·3 micron to 1·7 micron. These were found during a north-east wind, and must have been carried across the North Sea from the Continent of Europe.[1]

A record taken at Cheam, in Surrey, on December 29th,

[1] *Proc. Roy. Soc. A.* Vol. 101, 1922. "Suspended Impurity of the Air."

1921, during a wind north-west by north, gave 315 particles per cubic centimetre.

Micro-Chemical Examination

The fact that the efficiency of the jet depends upon condensation of moisture has made possible other methods of examination of the suspended matter of the air. Referring to the illustration of the apparatus, Fig. 33, it will be noticed that the damping chamber is of tubular form. When in use the apparatus is held by the pump; it was found that if the apparatus were held by the damping chamber a curious result was brought about. The heat of the hand caused moisture to evaporate from the damp lining of the chamber in greater quantity than the air could take up, and thus a fog could be detected inside the chamber. A record taken under such conditions was so affected by impact of the water drops as to be uncountable. The water flowed out sideways from the linear record, leaving the clear stream beds free from particles, which were stranded all round the margins of the little streams.

This fact was utilised to extend the operations with the instrument. When a large volume of air was drawn through the jet a perfectly opaque record was obtained, but if during the process the damping chamber was slightly warmed, the condensed water striking the record flowed out sideways in the manner already described. The soluble matter of the record dissolved in the condensed water and subsequently crystallised on the dried-up stream beds when the water evaporated. The crystals could then be examined microscopically and micro-chemically, and thus the nature of the salts forming them could be ascertained.

Acidity or Alkalinity

In view of the effect of the condensed water above referred to, it was thought that, by using a chemical indicator on the cover-glass upon which the record was taken, some information should be obtainable as to the acidity or alkalinity of the air. Experiments were made with cover-glasses coated

with a solution of gelatine in water, to which different indicators had been added. The indicators tried were methyl orange, Congo red, phenolphthalein, erythrosin (iodeosin). With regard to the methyl orange used in this way, the film was initially coloured either red or yellow, and it was found that the change from red to yellow, or *vice versâ*, on the surface of the film was not detectable. The same objection applied to Congo red, whereas with phenolphthalein, in which the colour change was from colourless when acid to pink when alkaline, the depth of colour obtainable with a thin film was not sufficient to be recognised under the microscope. A further objection was the absence of a characteristic colour for acid. Erythrosin was too difficult to apply, as it required to be dissolved in ether.

Following the experiment with gelatine a trial was made with filter paper coloured with methyl orange or Congo red. The method was to prepare some paper which had the characteristic colour for acid or alkali, but was as nearly neutral as it was possible to get, consistent with distinct coloration. Two half-discs of each paper were then cut and fixed on a metal ring of the same diameter as the cover-glass used in the jet apparatus. The ring was placed in the apparatus instead of the cover-glass, and in such a way that the linear record would be taken half on one paper and half on the other. This method gave some promising results ; a definite alkaline reaction was detected in one case. Only a few experiments on these lines have yet been carried out.

A third method used was to crystallise on to a cover-glass a little indicator from its solution, and to take the record on the cover-glass thus prepared, taking care to have the damping chamber warm while taking the record. Experiments made on these lines point to the method as giving the most sensitive and definite indications both of acidity and alkalinity. During the dense fog on Sunday, January 22nd, 1922, the reaction of the dust collected was decidedly acid to both Congo red and methyl orange. On the Friday previous to that date a definitely alkaline reaction was obtained. The acidity referred to does not necessarily imply the presence of free acid, as both methyl orange and Congo

red are sensitive to neutral salts, the latter particularly so to calcium salts.

Examination of Records by Volatilisation

Another method of examination applied to records obtained in London was as follows: A very dense record was made upon the cover-glass by drawing through a large volume of air, approximately 1,000 c.c. The cover-glass was removed; a shallow metal ring, about ·5 mm. deep, was then placed on top of the glass and covered by a second cover-glass. The lower glass was then heated gently over a gas flame, while a drop of water placed upon the exposed surface kept the upper cover-glass cool. After cooling, the upper cover-glass was removed, and a deposit was found on its surface of something which had been volatilised from the record and condensed upon the upper glass. On examination under the microscope this deposit was found to consist of small rounded drops of dark oily liquid, doubtless tar. This liquid was soluble in oil. No crystals were observed, but it is probable that by improved methods it will be found possible to obtain crystals volatilised from the record in this way.

It will be observed that the field for application of the new method is wide.

Other Methods

It may be useful here to describe shortly some other methods which have been used for dust measurement. A number of these are described in the *Journal of Industrial Hygiene*, Vol. I., No. 7, November, 1919.

Impact Methods

In most of these, dusty air is forcibly directed against surfaces specially prepared with sticky substances, such as glycerine, oil, gum, silicate of soda and resin. These methods have been used in different forms, and in most cases reliance has been placed upon some sticky substance to bring about the adhesion of the dust particles to the surface. There are

serious objections to the use of any such substance, which may be briefly summarised as follows :—

1. If a sufficiently high velocity is used to make the jet efficient, the sticky substance is blown away ; if the velocity is reduced, so as not to remove the sticky substance, the efficiency as a dust catcher is extremely poor.

2. When particles of dust are caught in a liquid or semi-liquid medium, they may become invisible if they are transparent and their refractive indices do not differ appreciably from that of the medium in which they are embedded, or they may be soluble.

3. It is very difficult to count records obtained in a sticky substance, as a microscope of low power must be used. It is impossible to get a reasonably accurate count without the use of an oil immersion, and such records do not lend themselves to this.

Filtration Methods

Soluble filters are used, such as sugar. Air is drawn through and the filter subsequently dissolved, a count being made from a small sample of the resulting solution. It is obvious that such a method will exclude all particles which are soluble in the liquid, or particles which are invisible in the liquid, owing to their refractive indices being similar. Filtration methods based on weighing can hardly be grouped under methods of dust counting.

Condensation Methods

Condensation of water on the dust particles is utilised in Aitken's dust counter and his koniscope ; a fog is produced and compared with a standard, or the drops are counted after they have fallen on a reticule. No distinction is made between dust particles and other nuclei which may be effective in assisting condensation.

Electrostatic Precipitation

This method has been used to trap the particles by precipitation of dust into a liquid ; the liquid is then com-

pared with standard suspensions. If the precipitation is on to a dry surface, the amount may be weighed directly, or an attempt to count under the microscope may be made.

A method of electric precipitation has been evolved by Professor P. Drinker and R. M. Thomson, in which an alternating current is employed without a rectifier. It is of the type intended for the examination of dust rather than its precipitation on a commercial scale. An outer tube of quartz or glass is coated outside with metal foil and acts as the collecting electrode. Axially in this is the precipitating electrode of wire in a small glass tube. Air is drawn through the larger tube by a side connection near the top and enters near the bottom. A voltage of from 1,000 to 20,000 is used, and the dust is caught on the outer tube.

For microscopic examination a piece of thin celluloid foil is rolled up and pushed into the tube to receive the deposit, and is subsequently removed and pieces cut off and mounted for examination. The dust is found to adhere firmly to the celluloid, and when suitably adjusted all the dust collects near the entrance of the air. It is only when not working effectively or at too low a voltage that the precipitate extends to near the top.

Agitation with Water

In Palmer's apparatus air is drawn at high velocity through 40 c.c. of water in a specially shaped vessel, which results in a great disturbance and production of spray ; the loss by evaporation is made good from time to time, and the water and suspended dust are finally made up to 100 c.c., and 1 c.c. of this counted in a cell after settlement.

Ultra-Microscope

Attempts have been made to count dust particles by an ultra-microscopic method, but the results obtained by the authors are not satisfactory. In counts which have been made in this way in a cell 3·5 mm. deep the number of suspended particles in the air was always less than the number obtained in the record of the jet. On December 1st,

1921, a record taken by the jet gave 11,300 particles per cubic centimetre, and an ultra-microscopic count at the same time gave only 4,400. An interesting point to observe as bearing on the visibility of small particles is that the number of particles in the above record larger than 0·85 micron was approximately 3,500 per cubic centimetre. It must be remembered that, in counting the deposit of the jet, a $\frac{1}{12}$-inch objective was used, while in the other a $\frac{2}{3}$-inch was used ; it is not possible to use a high power, owing to the working distance being very small, while the depth of the cell is necessarily considerable. Also, the Brownian agitation of the particles precludes the use of high magnification, because it magnifies the apparent velocity of movement and also reduces the field.

On January 22nd, 1922, during a bad fog in London, a count of a record taken by the jet gave 21,760 particles per cubic centimetre, while the ultra-microscopic method gave 18,750. There was an abnormal number of large particles during this fog, and it was observed that particles which settled to the floor of the cell used for ultra-microscopic count were from 0·5 micron to 0·9 micron in diameter, approximately, as measured under a $\frac{1}{6}$-inch objective. A serious drawback to the ultra-microscopic method is the extremely small volume of air which is examined. In the case referred to, the actual volume in which the particles were counted was approximately 1·6 cubic millimetre.

Settlement of Particles

Some methods of dust estimation depend upon the settlement of the particles upon prepared surfaces exposed in the open. A subsequent count of such particles obviously gives imperfect results, since it does not include suspended particles. It reckons simply dust which has settled on a plate during a given time, and the number need not be even proportional to the number in suspension. Everything depends upon the temperature and degree of disturbance of the air, size, shape and density of the particles, etc.

Measurement of Dust

The following is a bibliography of the various attempts to determine the amount of dust :—

Impact Methods

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Sugar.—11. Baskerville and Winslow. Report of Committee on School Inquiry. *Board of Estimates and Apportionment.* Final Report, 1913, 3, 608.

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Cotton Wool.—19. Same as (1).

20. Same as (3).

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Collodion Wool.—26. Same as (5).

27. Same as (13).

Cheese Cloth.—28. Same as (13).

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CHAPTER IX

FURTHER RESEARCHES WITH THE JET DUST COUNTER

The efficiency of the jet dust counter for collecting dust particles has been quantitatively investigated in respect of the variation due to: (*a*) Difference of pressure applied to produce the flow in the jet. (*b*) The width of the slot. (*c*) The depth of the cell. (*d*) The form of the cell. (*e*) The form of the slot.

The results afforded confirmation of the opinion that the dimensions and form of the standard instrument as described in Chapter VIII. could not be improved.

The Influence of Difference of Pressure in the Jet

The effect of variation of the pressure causing the flow through the jet was examined by forcing the air from a large bottle through the jet, the pressure in the bottle being measured by means of a manometer. The fact that the bottle contained water for forcing the air out assured the presence of sufficient water for condensation and made the use of a damping chamber unnecessary.

The result of this experiment showed that with low pressures of between 3 and 4 feet of water the percentage efficiency of the jet was low, something of the order of 50 to 60 per cent. of the whole number of particles being deposited, while as the pressure was increased to about 7 feet the efficiency rose to nearly 90 per cent. The efficiency referred to here is calculated from the result of records taken by a standard jet and hand pump from the bottle before and after the sample of air was forced through the experimental jet, the standard jet result being taken as giving 100 per cent.

The Influence of the Width of the Slot

Careful experiments were made as to the effect of width of slot upon the efficiency of the jet, as it was felt that there must be an optimum width, and it was desirable to ascertain this experimentally. For this purpose, pairs of records were taken, the first of each being taken with the standard jet of 0·1 mm. width, while the second was taken with another instrument, the width of slot in which was varied from 0·26 mm. down to 0·04.

The deposit from the experimental jet was compared with that from the standard, and the results were expressed as percentages of the number of particles recorded with the standard instrument.

As the width was reduced from 0·26 mm., a value was reached at about 0·1 mm. which gave a maximum efficiency, the efficiencies of the wider and narrower slots being below this.

The Effect of Depth of Cell

An instrument was prepared in which the depth could be varied from 1 to 3·2 mm., and records were taken for each depth and the numbers of particles obtained compared. Control tests were made during the experiment so as to provide for natural variation in the actual number of dust particles in the air. The result of this experiment showed that a cell 1 mm. deep gave the highest count.

The Form of the Cell

Tests were made with cells of different shape, and it was found that when a short slot of, say, 2 mm. length, was used it was still advisable to have a cell larger than 2 mm. diameter, that is, to determine the length of the slot by a 2 mm. diameter hole cut in the plate which forms the support to the cover-glass, the hole being enlarged to about 1 cm. for the upper half of its depth. This form of cell gave a better record and appeared to be more free from eddies and irregular deposition of dust than a 2 mm. cell.

The Form of the Slot

Experiments were made as to the best shape of slot for forming the jet, and particularly as to whether an attempt should be made to get stream-line approach by rounding the lower edges. It was found that no difference in efficiency was produced by using thick plates for the sides and flaring them out below to get a stream-line approach when compared with slots formed from thin sheets of copper with square edges to the slot.

The only difference noticeable between the two shapes of slot was that the record obtained with the stream-line entrance was somewhat narrower than when the edges were thin and square.

The efficiency of the standard instrument was further examined in two distinct ways :—

(*a*) By utilising two slots in series in the manner already described.

(*b*) By testing the air which had passed through the dust counter by means of a standard paper filter.

The results of both methods indicate that a very high efficiency was obtained, probably approaching 100 per cent.

Two Slots in Parallel

In a very dense smoke haze it is found that the numbers of particles present are so great that even with a sample of 50 c.c., the volume given by one stroke of the pump of the standard instrument, the dust particles are so thick on the record as to be difficult to count. In order to get over this difficulty, the volume of air drawn through the instrument might be reduced, or the slot increased in length. It was thought best to adopt the latter means.

Experiments were, therefore, made with an instrument which contained two slots parallel to each other, 1 cm. long, and separated by an interval of about 3 or 4 mm. Tests taken with this form of slot showed that it gave quite satisfactory results and enabled counts to be made when the single slot gave too thick a deposit. The efficiency of this form is probably not quite so great as of the single slot, as

there is some interference between the two jets in the escape of the air from the enclosure.

Method of Mounting Records

A satisfactory method of mounting the records for storing has been evolved. Provision is made in the instrument box for carrying a supply of microscope slides, to which are fixed thin rings of pure tin, coated with a special adhesive which remains tacky, so that, after a record is taken, all that is necessary is to place the cover-slip on the ring with the record downwards, and press gently into position ; the cover-glass is at once sealed down firmly, so that it is impossible to remove it without warming.

Tin rings are used because they lie flat on the slide, are easily obtained, and show no tendency to buckle when coated with adhesive, as is the case when paper rings are used.

Mounting Medium

Many cements were tested before a satisfactory mixture was obtained. Canada balsam in xylol was unsuitable, because it was difficult to apply and required far too long a time to harden ; also, since it contained a volatile solvent, it promoted the condensation of drops on the enclosed face of the cover-glass. Marine glue was open to similar objections. Attempts to dilute Canada balsam to a sticky consistency with a non-volatile substance, such as high-boiling paraffin or vaseline, were unsuccessful, since the balsam would not mix properly and the product would not remain tacky.

A mixture of resin and vaseline at first appeared promising. These constituents mix readily when melted together, and in suitable proportions produce a cement of the consistency of pitch, and sticky on cooling, so that the slips could be mounted without difficulty. This mixture, however, after two or three weeks became opalescent and hard, as if crystallised. Finally, a mixture of high-boiling liquid paraffin and pure resin was tried and found fairly satisfactory. It is essential that light amber-coloured resin be

used, otherwise the mixture rapidly deteriorates. The following is the best composition for the adhesive :—

Pure resin about	78·5
Liquid paraffin about . . .	21·5

This mixture is readily melted to a quite mobile liquid, into which the tin rings may be dipped and then placed upon warm clean microscope slides. The tin rings adhere very firmly on cooling, and the cement becomes sufficiently hard for the slides to be cleaned without any danger of smearing. When the cover-slip is placed on the ring, the warmth of the hand is sufficient to soften the adhesive enough to make it retain the slip.

This cement contains no volatile constituent and is fairly stable. A slight difficulty has however arisen in connection with its use since it is found that in warm weather there is a tendency for the rings, with their records attached, to slip on the surface of the glass; but this only occurs when the slides are stored edgewise, and may be prevented by storing the slides with their rings and adhesive on the flat. The preparation is somewhat sensitive to temperature as regards its fluidity, and if made sufficiently hard to avoid slipping during warm weather, it will probably be too hard for use during cold weather or at night.

Another difficulty of the resin adhesive developed with its use; it showed a tendency to harden after a few weeks, and sometimes the cover-glasses were detached from the slides by a slight jar. In this way some very valuable records were lost, and a modification was made in the adhesive used for mounting. A more satisfactory adhesive was made from asphaltum melted and softened by the addition of a little liquid paraffin. This mixture does not show the same tendency to harden as the resinous adhesive, nor to flow when the slides are placed on edge.

An alternative method to this was also adopted, in which paper rings of about one-half to a millimetre thick are first stuck to the slide by any liquid glue. Then, for mounting the cover-glass, three or four very small spots of liquid glue are placed equidistantly around the ring and the cover-glass laid on top. This method has the advantage that there is no

likelihood of condensation occurring upon the under surface of the cover-glass, as it is not hermetically sealed; it is useful also as being available when the supplies of special adhesive have run out, as any liquid glue such as is sold in collapsible tubes is suitable. The chief drawback to the method is, however, that the cover-glass has to be left intact for some time after mounting before it can be cleaned for examination, as the glue does not harden immediately. This is not the case when using the special asphaltum adhesive, as the cover-glass adheres to this at once sufficiently to be handled and cleaned without being disturbed.

These last two methods of mounting were ultimately found to be the most satisfactory.

Counting of Records

In the ordinary method of counting the records a $\frac{1}{12}$-inch oil-immersion objective is used, and it is found that the time required for counting one record may vary from ten minutes to half an hour, depending upon the number of dust particles.

Attempts have been made to simplify the method of counting and to avoid the use of an oil-immersion objective. Using a $\frac{1}{6}$-inch objective, that is, 4 mm., and a suitable dark ground illumination, it was found that a count could be obtained which compared favourably with that obtained with the oil immersion, but that the number of particles visible depended greatly upon the intensity of the illumination. For example, to get a count in this way comparable with that obtained when using an oil immersion, it was necessary to use a pointolite lamp and a large condenser, but this is, of course, not convenient in most cases.

One great objection to using the dark ground illumination is that it gives no idea as to the size or the shape of the particles; all particles below a certain dimension show as discs, their brightness varying with their size. Attempts were made to produce a standard for comparison with the records by putting black spots upon a white card, the number of spots being known, and their dimensions being about the same as of the dust particles found in the air when viewed through a $\frac{1}{12}$-inch objective. It was intended to use this

standard card as follows. The record to be counted having been placed upon the stage of the microscope, the microscope is bent to a horizontal position and the image projected upon a white surface adjoining the standard card ; a comparison between the card and the image is thus made possible. Alternatively, by use of a fitting on the eyepiece of the microscope, such as is designed for drawing specimens, the image of the record may be seen superimposed upon, or close beside, the standard card.

The method proved of little use, as the variation in size of the particles of dust was so great that no single standard card could be made to represent them satisfactorily.

Another method tried was to obtain a standard record, one centimetre long, and varying in density from end to end, and to count the number of particles on this record at different positions in its length. It was intended then to compare with this as standard the record to be counted, by the use of a low-power objective and a dark ground illumination. It was found that a standard record of this type could be easily obtained by using a slot of width varying from 0 at one end to 0·1 mm. at the other, and 1 cm. long. This gave a record of the desired form, but there was great difficulty in comparing it with the record to be examined, at least when using a monocular microscope, as one record was necessarily above the other, and, therefore, both could not be in focus simultaneously. It is possible that, by use of a binocular microscope, the comparison could be made, but this did not seem to be any improvement over the use of a single-tube instrument with oil immersion. The method of counting still found the best is that described in Chapter VIII., *i.e.*, by the use of a $\frac{1}{12}$-inch objective with oil immersion, and a reticule micrometer eyepiece.

Use of Polarised Light

One of the difficulties in examining records by polarised light arises from the small size of the particles, which makes them practically opaque. Certain of the larger particles have been examined satisfactorily under polarised light. For example, in the case of the spherical particles, to which

reference is made later, it has been found that under a very bright polarised light a brush formation is clearly shown, which appears in the form of a dark cross in the spheres. It differs from the brushes observed in crystals ; when the stage is rotated, carrying the particle with it, the brush remains in the same position instead of revolving, as it would do with a crystal. After these observations had been made, reference was made by Mr. Conrad Beck, in a paper before the Royal Microscopical Society, to a similar appearance which he had observed when small mercury globules were examined under polarised light in the same way. He attributed the appearance to elliptical polarisation by reflection from the surface of the globules, and concluded that the only inference which could be drawn from the presence of brushes of this kind was that the particles had reflecting surfaces. A somewhat similar effect has been observed in drops of liquid on the under surface of the cover-glass.

Apart from this effect it is rarely possible to detect any reaction to polarised light ; and doubtless this is due partly to the nature of the particles in city air, as well as to their small size. Occasionally a bi-refringent particle is seen in the record, and probably there would be a greater number near a source of siliceous dust. In connection with the use of polarised light, it has been found that with the excessively small particles of dust a very powerful light is necessary if any result is to be obtained.

Mechanical Stage

For counting the records it is almost essential to have a mechanical stage, in order to be able to move the record slowly across the field. In addition to this, it is advisable to have some means whereby the record can be set at right-angles to one of the traversing movements. This implies a revolving plate placed above a mechanical stage so as to be moved with it, a combination rarely found in standard microscopes. For this reason a stage has been designed by Dr. Owens which can be fitted to any microscope. In this there is a traversing slide actuated by a screw with a milled

head, and fixed in this slide is a revolving disc which receives the microscope slip with its record and permits it to be set in any position relative to the direction of movement of the slide. Having set the record at right-angles to the direction of movement, the screw with milled head enables it to be shifted across the field of the microscope. The whole fitting is intended to rest upon the stage of an ordinary microscope, where it is held in position by the usual stage clips. The stage is illustrated in Fig. 36. Another way out of this difficulty has recently been adopted. The cell in the dust

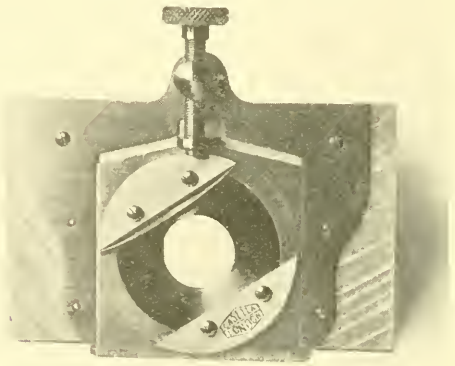

Fig. 36.—Mechanical stage designed to facilitate counting with a microscope.

counter, which is circular, is in the new instruments made with recesses in its rim to take the corners of square cover-glasses, so that either square or round may be used. With square glasses the record is easily mounted across or along the slide, and so requires no adjustment to the mechanical stage movement.

Instruments in Use

Under a provision made by the International Union for Geodesy and Geophysics in Rome, 1922, jet dust counters have been sent to the meteorological offices of Athens, Bucharest, Japan, Lisbon, London, Madrid, Paris, Warsaw,

Rio de Janeiro, Rome, Stockholm, Toronto ; the Weather Bureau, Washington ; Baron de Dorlodot, Belgium ; the Meteorological Bureau, Melbourne, Australia ; and the Geophysical Observatory, Pavia, Italy.

The intention was for observations to be made on certain days selected for international meteorological observations, and to be reported to the Bureau of the Meteorological Section of the Union. A considerable number of observations were reported at a meeting of the Union at Madrid in 1924.

Instruments have also been acquired for private use by persons interested in the study of atmospheric dust. A notable report has been made to the Factory Department of the Home Office,[1] entitled " Report on the Grinding of Metals and Cleaning of Castings, with Special Reference to the Effects of Dust Inhalation upon the Workers," by E. L. Middleton, M.D., D.P.H., and E. L. Macklin, O.B.E. Many dust records taken with the jet dust counter are described in this report.

Some Typical Results

Some of the results obtained with the dust counter are embodied in the Table which follows. The majority of the observations were taken by Mr. G. M. Watson, A.R.C.Sc., Dr. Owens' official assistant in the inquiry, whose technical ability and enthusiasm for the work earned the admiration of the Advisory Committee, and whose untimely death on April 9th, 1925, after a long illness is deeply regretted.

Others were taken by Mr. E. G. Mariolopoulos, of the Royal Observatory of Athens, who was at the time attached to the School of Meteorology at the Imperial College of Science and Technology. The rest were by Dr. Owens himself. Many of these records were taken in London during smoke fogs, from which it will be observed that the number of particles in a smoke fog varies from between 20,000 to something over 50,000 per cubic centimetre. Under the column headed " Remarks " the dimensions of the particles are given, and it is of interest to note the variation in maximum diameter. There appears to be a tendency for the

[1] Published by H.M. Stationery Office.

TABLE OF RESULTS OBTAINED BY THE JET DUST COUNTER

Date.	Place of Observation.	Time, British Standard Time.	Number of Particles per c.c.	Maximum Diameter of Particles.	No. of Transparent Spheres per c.c.	Maximum Diameter of Spheres.	Remarks.
1922.				Microns.		Microns.	
Feb. 7th	Westminster . .	Afternoon	5,580	0·75	—	—	Normal days for this time of year.
,, 8th	,, . .	,,	11,600	—	—	—	Records taken inside an office, near an open window.
Mar. 7th	,, . .	,,	7,720	0·75	Many	1·2	
,, 16th	,, . .	,,	11,800	0·75	Many	1·2	
Mar. 18th	Cheam (Surrey) .	Afternoon	1,200	0·75	66	1·5	Many spheres 1·25μ diameter.
,, 20th	Westminster . .	1 p.m.	17,200	0·75	410	1·5	Records taken out of window.
,, 20th	,, . .	4.30 ,,	8,450	0·75	212	1·5	
,, 26th	Bloomsbury . .	1.45 a.m.	5,200	0·75	106	0·9	Taken from fourth floor window.
,, 27th	South Kensington .	12.15 p.m.	5,100	0·75	80	1·2	Spheres generally not more than 0·9μ in diameter. Occasional irregular particles up to 1·2μ diameter.
April 1st	South Kensington .	10.10 p.m.	4,500	—	53	1·2	Average diameter of spheres = 0·9μ.
,, 2nd	,, .	4.15 ,,	3,260	—	40	1·2	Average diameter of spheres = 0·9μ. Many crystals present.
,, 3rd	Westminster . .	1.30 ,,	14,000	—	175	1·5	Average diameter of spheres = 1·2μ. Snowing heavily at 1.30 p.m.; no snow at 3.45.
,, 3rd	,, . .	3.45 ,,	14,100	—	175	1·5	
,, 5th	South Kensington .	12.30 ,,	4,140	—	53	1·2–1·5	
,, 5th	,, .	4.30 ,,	2,400	—	26	1·2–1·5	
,, 6th	,, .	9.45 ,,	19,140	—	437	1·5	Not hygroscopic. No crystals.
,, 7th	,, .	9 ,,	7,820	—	66	1·2	Nothing on the record > 1·2μ in diameter.
,, 8th	Kew Gardens .	2.30 ,,	900	0·75	0	—	Fine and sunny. Strong wind.
,, 9th	Bloomsbury . .	12.30 ,,	9,440	0·75	146	1·5	Calm. White haze. Spheres from 0·75μ diameter down.
,, 11th	South Kensington .	10.25 ,,	4,160	0·75	0	—	Well-formed rhomboidal crystals present, up to 15 microns long.
,, 12th	,, .	2 ,,	4,250	0·75	40	1·5	Raining steadily. Skeletal crystals present. Most particles less than 0·75μ diameter.

April 17th	Grimsby . .	4.30 ,,	1,960	0·75	148	1·2	Wind N. 50 per cent. of particles rounded and 0·75μ diameter.
,, 18th	Healing (Lincs.) .	11.30 a.m.	Trace	—	—	—	Strong wind from N.N.E. Sun shining, but cold. A few drops only present, and practically no smoke particles.
,, 19th	Bridlington . . (Head of Pier.)	5 p.m.	0	—	—	—	Gentle wind from E.N.E. Sunny and cloudless. Visibility perfect. Drops and crystals only present; rhomboidal, needles, and hexagonal plates. No square crystals, and no smoke particles, even in 3,000 c.c. record.
,, 20th	1 mile E. of Flamborough Head.	3.30 ,,	0	—	—	—	Drops and small crystals only. Almost dead calm. High cirrus clouds moving slowly from E. Sun shining.
May 30th	South Kensington .	10.25 a.m.	5,100	0·75	—	0·9	Moderate haze.
,, 31st	,, .	10.5 ,,	4,100	0·45	25	0·9	No wind. Hot and sunny.
Aug. 25th	Holme, Norfolk .	12.30 p.m.	1,145	1·5	0	—	Particles generally less than 0·75μ diameter. Strong N. wind. Showery. Visibility poor.
,, 29th	,, .	10 a.m.	930	1·20	0		Wind S.W. Visibility bad. Many particles rounded, and 0·75μ diameter. Many drops on record.
Sept. 2nd	,, .	12 noon	152	—	—	—	Light wind N.E./N. Hazy. Visibility bad.
,, 5th	Brighton . .	12.10 p.m.	1,380	—	—	—	Wind N. Overcast. Heavy haze.
,, 7th	Hull . . .	7.30 a.m.	4,830	—	—	—	Thick water fog.
,, 8th	,, . . .	7.15 ,,	8,100	—	—	—	Wind N.E./N. Smoke haze only.
,, 10th	,, . . .	6.30 p.m.	3,080	—	—	—	Wind N.E./N. Clearer.
,, 11th	,, . . .	7.30 a.m.	13,800	—	—	—	Wind W. Smoke haze.
,, 11th	Outside Spurn Point	4.30 p.m.	140	—	—	—	Haze visible over land.
July 11th	Cheam . . .	8.40 a.m.	920	—	—	—	Little or no wind. Marked haze.
Oct. 26th	South Kensington .	10.5 ,,	33,400	1·5	—	—	Thick fog. Lachrymatory until 11.30 a.m.
		10.30 ,,	35,700	1·5	—	—	Pale yellow at 10.5 a.m. Deeper yellow at 10.30. Whitish at 11.5. Began to clear at 11.5. Fog white, and rapidly clearing at 11.30. Most of particles brownish and tarry-looking, from 0·75μ to 1·2μ in diameter, from 10 to 11.45 a.m. Many black spheres. 0·75μ diameter at 2.50.
		11.5 ,,	37,000	—	—	—	
		11.45 ,,	27,900	1·5–2·25	0	—	
		2.50 p.m.	6,085	0·75	95	0·9	

TABLE OF RESULTS OBTAINED BY THE JET DUST COUNTER—*continued*

Date.	Place of Observation.	Time, British Standard Time.	Number of Particles per c.c.	Maximum Diameter of Particles.	No. of Transparent Spheres per c.c.	Maximum Diameter of Spheres.	Remarks.
1922.				Microns.		Microns.	
Sept. 27th	South Kensington .	9 a.m.	1,855	—	—	1·2	A few crystals present. Some transparent spheres 1·2μ diameter.
		10 ,,	1,815	—	—	0·9	Some transparent spheres 0·9μ diameter.
		11 ,,	1,150	0·3	—	0·9	
	(Roof of building, 80 feet high.)	2 p.m.	3,580	0·3–0·6	—	1·5	Many black spheres 0·6μ diameter.
		3 ,,	4,200	1·4	—	1·2	Many water drops. Few spheres only.
		5 ,,	5,326	1·2	—	2·5	Some black spheres 2·5μ diameter.
		6 ,,	6,390	0·75	—	1·2	30 per cent. of total are black spheres, 0·75μ diameter. Many particles 0·45μ diameter.
Sept. 27th	(Roof of building, 80 feet high.)	7 p.m.	8,080	0·45	172	1·5	30 per cent. of total are black spheres from 0·45μ to 0·75μ in diameter. Many particles on lower limit of visibility.
	(Ground level.)	7 ,,	8,800	0·45	172	1·5	
Sept. 26th	South Kensington .	2 p.m.	1,126	0·75	—	1·2	Few transparent spheres. Very few > 0·75μ diameter.
Nov. 3rd	,, .	10.15 a.m. and 11.0 a.m.	15,500	1·5	0	—	Moderate smoke fog. Some aggregates. Many brownish tarry, irregular particles, very variable in size and shape. No spheres. Majority of particles less than 0·75μ diameter.
1922.							
May 23rd	Westminster . .	—	1,390	—	—	—	Ordinary non-foggy day.
1921.							
Jan. 22nd	,, . .	2 p.m.	21,760	3	—	—	Dense fog. Many particles brownish and tarry, 1·7μ in diameter.
Oct. 26th	,, . .	10 a.m.	20,800	1·7	—	—	Moderate smoke fog. Buildings invisible against sky at 1,600 feet.

1923.						
Jan. 17th	Westminster . .	11.15 a.m.	53,000	—	—	—	Very dense fog. Limit of visibility 30–40 yards.
Feb. 22nd	Sheffield . .	9 ,,	29,500	0·75	—	1·5	Many spheres, bean-shaped particles and crystals. Record looks very tarry.
Mar. 5th	South Kensington .	12 noon	4,265	0·75	50	0·9	Non-foggy day. Very few present > 0·75μ diameter.
Mar. 23rd	Leixoes Harbour .	10.30 a.m.	250	0·75	0	—	Slight haze. Visibility poor. Wind N., very light. Particles excessively small—most on limit of resolution of microscope.
Mar. 27th	On Guadiana River	8 a.m.	90	1·5	0	—	Wind N., very light. Visibility good. Slight haze. Crystals present, but very badly formed.
		9.40 ,,	15	0·75	0	—	No wind. Visibility good. Haze nearly gone. No crystals or spheres, and record not hygroscopic. Particles black, and irregular in shape.
		11.20 ,,	16	0·75	0	—	Wind S., very light. No crystals, but record hygroscopic.
April 1st	San Domingos .	4.15 p.m.	69	0·75	0	—	No wind. Smell of tar at time of taking record. 110 yellowish drops present per cubic centimetre, approximately 3μ in diameter, many containing sugary-looking masses of crystals.
April 23rd	Off Finisterre .	8 a.m.	43	0·75	0	—	Raining. Haze on land. Wind N. Occasional crystals evidently NaCl, of edge 1·8μ.
,, 24th	Middle of Bay of Biscay.	2.30 p.m.	15	—	0	—	Tabular and needle-shaped crystals present, needles up to 13μ long by 0·9μ wide. Wind N.N.E. and visibility good. Weather clear and sunny.

particles to attain a maximum size during heavy smoke fogs, whereas during the lighter hazes the particles are usually much smaller.

A few interesting occasions may be noted :—

July 28th, 1922, at Cheam, in Surrey, was a bright sunny morning, with a very thick haze and little or no wind. At 8 a.m. G.M.T. a circular jet of about 0·1 mm. diameter had 1,500 c.c. of air drawn through it, and where the jet impinged upon the cover glass, 1 mm. away, a small conical pile of dust was deposited with a sharp point at the top. The height of the pinnacle was approximately 0·044 mm., and the diameter 0·16 mm. The appearance is described in the notes as suggesting a small volcano ; the centre part, looking dead black and shiny, was surrounded by a narrow brown boundary, outside which was a light yellow ring, and in the ring were numerous crystals. This showed that there was a large amount of solid matter in the haze, together with a certain amount of crystalline salts, and that the haze was due, to a large extent, to solid matter. There was no great evidence of the presence of liquid, which in quantity would certainly have washed away or prevented the formation of the pinnacle of dirt. This is important in connection with the question of the formation of haze by the action of hygroscopic nuclei, which is referred to later on.

The cover-slip with the pinnacle of deposit was heated on a piece of metal in a Bunsen flame, and immediately above the pinnacle, separated from it by about $\frac{1}{2}$ mm. by means of a metal ring, a second cover-glass was placed and kept cool by being moistened with water. After about two minutes the whole was removed, and the pinnacle of dirt was left exactly as before, but it had lost its shiny appearance and become dull, like lamp-black. Crystals were still present, quite dry and sharply defined—some of a skeletal form. The upper cover-glass had upon it a collection of drops condensed in a circular patch ; each drop was seen under the $\frac{1}{12}$-inch objective to contain smaller spheres of different material, of an oily appearance. The cover-glass was then reversed, and the drops rapidly evaporated, leaving the oily matter behind. On breathing upon the sublimate, the large

drops were re-formed round the small particles which otherwise remained intact. The cover-glass was then washed in xylol, but the oily looking particles still remained.

On January 29th, 1922, at Cheam, during a bright sunny day with a good breeze from the west, there was very little haze. A jet with a slot 10 mm. in length was fixed to a filter pump and air was drawn through for forty minutes. A record was obtained containing abnormally large particles,

Fig. 37.—Organic particles obtained from the air of Cheam, Surrey, January 29th, 1923.

some spheres, some crystals, some black, and some yellowish and transparent, with a definite structure, such as shown in Fig. 37; these varied in size from 10 microns long by $7\frac{1}{2}$ microns wide to 24 microns long by $7\frac{1}{2}$ wide.

On August 5th, 1922, at Cheam, there was a thick white fog in the morning; the temperature was 55·5° F., the wet bulb 54·5° F.; very light east wind. Air was drawn through the jet for half an hour, and a dense black record was obtained. This was at 7 to 7.30 a.m. G.M.T. A similar record at 8 to 8.30 was obtained and heated in the manner

already described. On the upper cover-glass a little yellow oily liquid was condensed. Clearly the fog contained much sooty matter.

On August 11th, at Cheam, air was again drawn through for half an hour from 8.5 to 8.35 a.m. G.M.T.; little wind, sky overcast, dense haze, very cold; dry bulb 51° F., wet bulb 50° F.; no damping chamber was used. A dense black

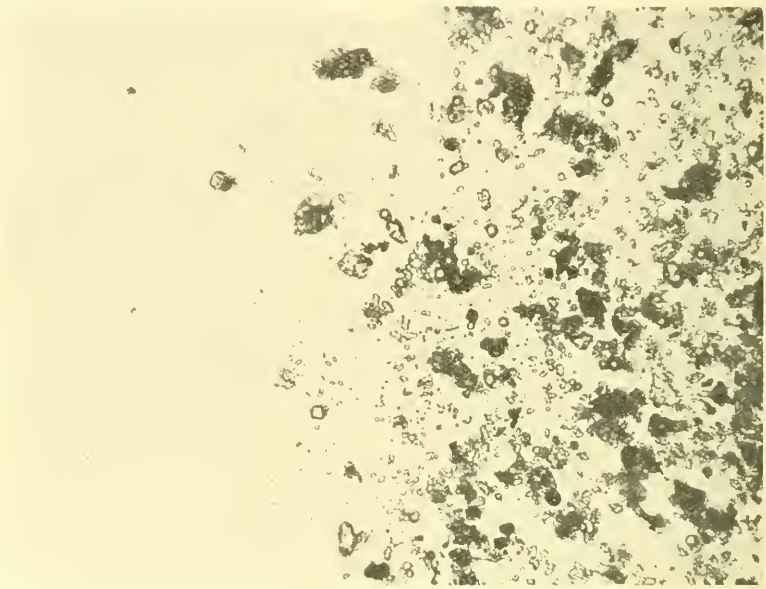

Fig. 38.—Particles from the air of Cheam, Surrey, on August 11th, 1922. Magnification, 500 diameters.

line was formed on the cover-glass, and on the edges of this were numbers of rhomboid crystals. On volatilising this record a cloudy-looking mark was formed on the upper cover-glass, following the line of the record. This was resolved under the microscope into a number of very small black particles. A photograph of the record with crystals is shown in Fig. 38, and a photograph of one portion with higher magnification in Fig. 39. A second record was taken on the same day with the damping chamber in position. This also gave a thick black record, which became lighter

on heating, showed numerous stream beds and plenty of crystals, nearly all rhomboidal and very well formed ; there were also a number of skeletal crystals in the dried-up stream beds. The material condensed from this on heating appeared also as numerous round black dots : as in the first record, no oil was visible.

A record taken under somewhat similar conditions at

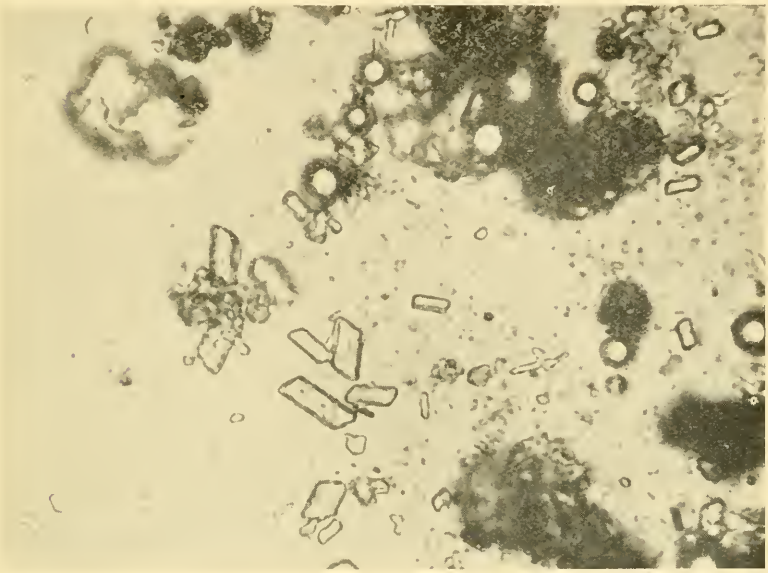

Fig. 39.— Part of the record shown in Fig. 38, but magnified 1,750 diameters.

Cheam on August 14th, during a thick haze, showed numerous irregular black particles and crystals similar to those described above.

At Hull, on September 11th, 1922, two interesting records were obtained ; the first was taken at the edge of the river at 7.30 a.m., with a west wind and a thick smoke haze covering the river, the opposite bank being invisible. This record gave 13,800 particles per cubic centimetre. On the same day, at 4.30 p.m., a second record was taken outside Spurn Head, during which a thick haze was observable lying over the land. This gave 140 particles per cubic centimetre. The

comparison of these two gives an indication of the amount of impurity added to the air in Hull.

On November 13th, 1922, at Cheam, there was a dense fog through which objects on the ground were not visible beyond about 70 yards. At the same time it was observed that the sun's disc was clearly defined and red, and could be seen through a line of trees about 100 yards distant. The trees themselves were entirely invisible in the fog, except over the sun's disc, where the branches and even the finest twigs were perfectly clearly defined on the circle of the sun's disc.

In London, on the same day, at 1 p.m., there was a dense fog, and a record taken there gave 39,000 particles per cubic centimetre.

Probably the densest fog experienced during the winter in London was on January 17th, 1923. The number of particles per cubic centimetre at 11.15 was about 53,000, the diameter varying from 1·5 microns down. There were numerous crystals visible in this record.

A number of records were taken by Dr. Owens during a visit to Portugal, which are referred to in detail under "Hygroscopic Nuclei," p. 180. An attempt was made to ascertain the amount of salt in the air at different distances from the sea.

Many of the records in the Table, pp. 161–163, were taken in connection with a research on visibility for the Advisory Committee on Atmospheric Pollution, which is not yet completed.

A record taken of the smoke from a wood fire presented a curious appearance: where the jet struck the cover-glass there was a thick brown, tarry-looking deposit having a granular appearance. This was surrounded by an irregular mass of drops, apparently of tar. In the deposit there were several transparent colourless patches, perfectly rectangular in shape and evidently crystalline. These are illustrated in Fig. 40. A needle-shaped crystal penetrated one of the rectangles like a skewer.

Records obtained from tobacco smoke show nothing but transparent yellow oily deposit free from solid particles.

In order to give some indication of the usual size of the

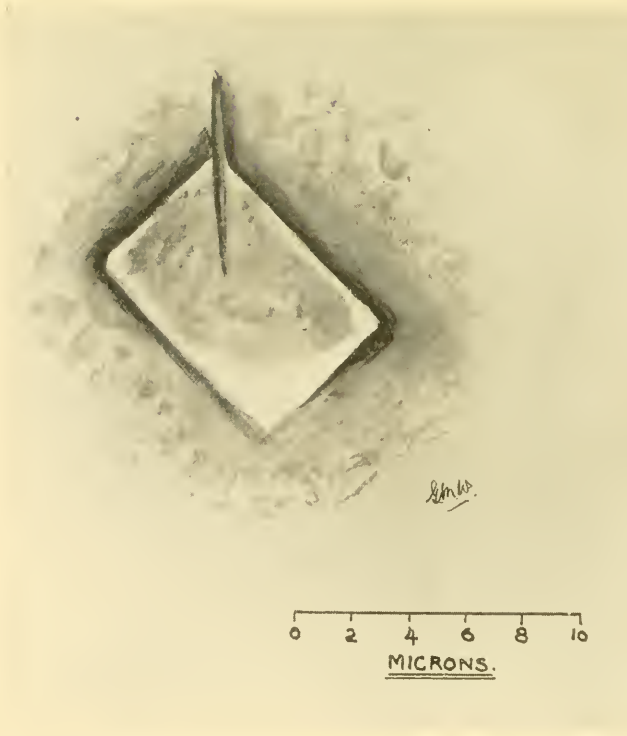

FIG. 40.—Crystal in a record of smoke from a wood fire.

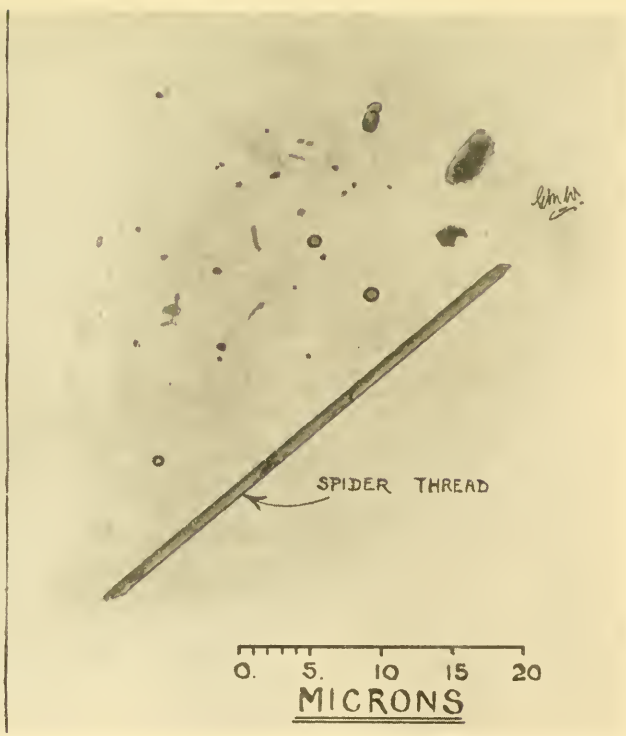

FIG. 41.—Typical smoke haze particles compared with a spider's web.

particles forming a London smoke fog, a photograph was prepared of a spider's web stretched across a record, so that both the particles and the web could be seen simultaneously. This is illustrated in Fig. 41. The diameter of the spider's web was approximately ten times that of the particles of dust trapped on the record. Thus it appears that during a heavy smoke fog in London a man would breathe in the course of twenty-four hours of such a fog 500,000,000,000 particles of suspended matter. Their size is such that, if placed in contact, these would form a string of about 250 miles in length. This way of looking at the degree of pollution of the air gives some idea of the work which must be done by the cilia and cells of the respiratory organs to remove the impurities breathed in.

Spherical Particles

It is common to find in most dust records in England a variable number of transparent spherical particles mixed with the ordinary irregular dust particles. These vary in diameter from about $1\frac{1}{2}$ microns downward, and the number present fluctuates considerably. For example, early in March, 1922, the number present in London began to increase, and towards the end of March reached something like 50 per cent. of the total dust count. When very small, these particles have the appearance under the $\frac{1}{12}$-inch objective of opaque dark discs, but the larger ones show as black circles with bright spots in the centres. For example, when below a diameter of 0·75 micron there are no bright centres, and the particles appear black. This is probably an optical effect, and would occur even if the spheres were made of transparent material. With the larger spheres an object placed under the condenser gives a sharp recognisable image through the spheres; the thin supports of a stop in the carrier of the condenser were quite recognisable, and the image formed was about $\frac{1}{2}$ micron above the spheres (Fig. 42).

The presence of an unusually large number of spherical particles in the atmosphere was first observed on March 16th, 1922, when a record in Westminster showed 50 per cent. of spheres. A local source was suspected, but records taken on

March 18th and 19th, in Surrey, twelve miles from London, showed similar spheres. Again, records taken twenty miles north of London, at St. Albans, on March 26th, 1922, showed the same phenomenon, although the wind was blowing from the north, and, therefore, could not bring particles from London. The occurrence of large numbers of such spheres has been observed on many occasions since. They are usually

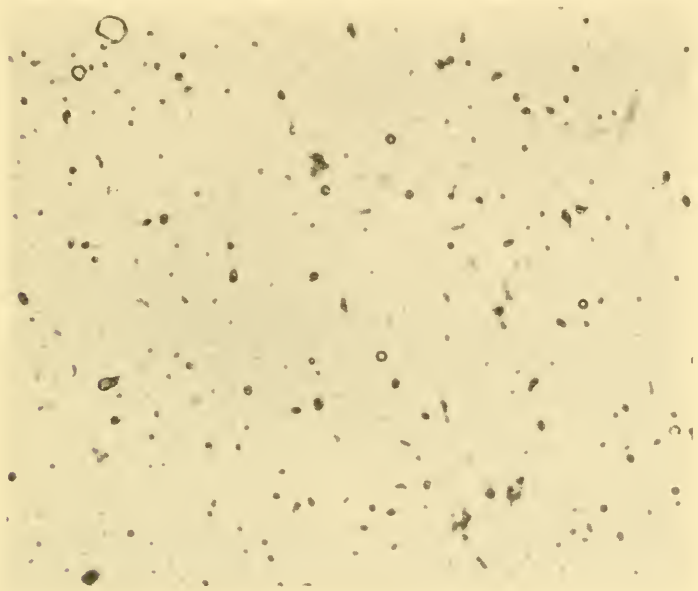

Fig. 42.—Record of London smoke haze, March 26th, 1922, containing transparent spheres. Magnification, 2,000 diameters.

transparent and colourless, but sometimes reddish-brown in colour.

Refractive Index.—Experiments were made on the refractive index of the spheres by comparing with Canada balsam, in which they were mounted: the refractive index was a little lower than that of the Canada balsam, that is, something under 1·54. An effect of the high refractive index is seen in the appearance of the particles when mounted dry. The dark band surrounding the bright centre varies with different materials; for example, artificially formed spheres, to be

referred to later, showed up as transparent when of smaller diameter than those obtained in the dust records.

Solubility.—The spheres have been tested for solubility in water, xylol, and cedarwood oil. They are not soluble in any of these, nor are they hygroscopic.

The fact that they are not soluble in water was shown by several methods ; for example, a record some weeks old was found to have become covered with drops of moisture, and occasionally spheres were included in the drops, but remained undissolved. Again, records taken when the damping chamber of the instrument was warmed showed evidence of large quantities of condensed water, so that streams were blown out to each side of the record. This peculiarity has been referred to already, and it is possible to observe in the dried-up beds of these lateral streams crystals of the soluble salts contained in the dust. Sometimes, however, in addition to these crystals, it has been observed that the end of a stream has a large number of spherical particles, evidently washed there by the water and stranded as the latter evaporated.

Examination under Polarised Light.—The spheres are not visible under crossed nicols except when a very intense light is used and the spurious brush effect is developed, which was referred to on p. 157.

Staining.—Attempts have been made to stain the particles by methylene blue in water and in glycerine jelly, but they showed no indication of taking up the stain. The dye was caused to flow under the cover-glass while the spheres were kept under observation ; it was subsequently removed with blotting paper and the record washed by drawing water under the cover-glass, after which the spheres retained their original colourless appearance. The same experiment was tried with picro carmine, Nicholson's blue, aniline blue, gentian violet and eosin, without effect. The Gram method of staining was also tried without effect.

Pressure.—Attempts were made to compress a record containing spheres, and after some difficulty it was found possible to flatten out the transparent spherical particles into semi-transparent granular-looking discs, and these discs were

found to take up stain easily. This may have been due to a powdering of the particles and absorption by capillarity, or alternatively, if the sphere was contained in a resistant skin, the rupture of the skin may have exposed the part inside to stain. Against the capillarity theory it should be noted that the stain was introduced after the compressed particles had been covered with water.

Heating.—To find the effect of heating, records were taken in duplicate and the number of spheres in one of them counted; the second record was heated to 100° C. for different periods from fifteen minutes to three hours, and the number of spheres in it counted for comparison with the unheated one. In a particular case the unheated record showed 240 transparent spheres per cubic centimetre, of diameters from 0·75 to 1·2 microns; the heated record showed only eighty spheres per cubic centimetre, and all these were between 0·75 and 0·85 micron in diameter. The larger sized spheres had disappeared. This would seem to indicate that the spheres are of two different kinds at least.

Again, the record which had been examined and the number of spheres noted was heated to redness, after which some of the spheres remained unaltered, while most of the other particles had been burned away completely. In this case also some of the spheres disappeared, while others resisted heating.

Drying.—To find the effect of drying, a record containing spheres was sealed on its tin ring, and allowed to stand for several days, with a little phosphoric anhydride inside the cell. On examination the spherical particles were unaltered in appearance.

Culture Tests.—Attempts were made to grow the spheres by mounting a record in a solution of gelatine with a little sugar added, and the appearance of the particles certainly altered, but it is very doubtful if this was due to growth. Some of them showed what appeared like a development of nuclei, while others showed buds. This may have been due to some change in the culture medium rather than in the particle. The change occurred within ten minutes of mounting, and it is, therefore, unlikely to have been due to growth,

but may have been due to some change in the gelatine. The records were kept in the culture medium for two or three days at a temperature of 70° F., but no further change occurred.

Artificially-produced Spheres.—A record of fumes taken in an analytical laboratory (Fig. 43) showed large numbers of spherical transparent particles, probably ammonium salts,

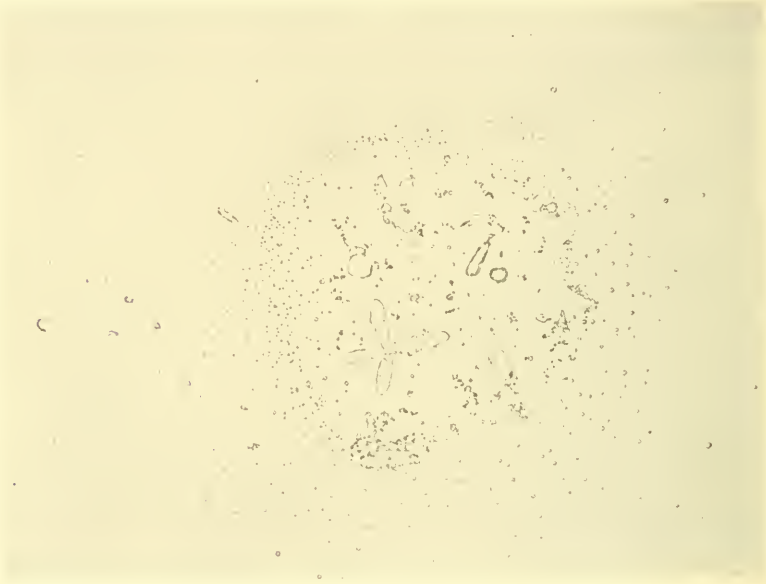

Fig. 43.—Part of a record taken in a chemical laboratory showing the end of a stream bed with crystals and spherical particles. Magnification, 660 diameters.

but these are soluble in water, and crystallise out of solution into larger crystals of a definite shape, and cannot, therefore, account for the spheres found in the ordinary air.

Examination of furnace ash and soot, or ash discharged from chimneys, shows large numbers of transparent spheres, but usually they are of great diameter compared with the ones now under consideration, varying, in fact, from about 1 mm. in diameter down. These particles, composed of fused ash, are of a variety of colours from transparent glassy-looking to brown, or reddish-brown balls, evidently stained

with iron. It has been found that the ash produced by pulverised fuel furnaces is very rich in such spheres ; in fact, it is sometimes chiefly composed of them. The method of burning in this case is peculiarly suitable for the production of spheres from the fused residue of the coal, as the pulverised coal is blown into the furnace with an air jet, and it is the aim of the designer to have the furnace of such dimensions that the coal will be completely burnt out and the ash cooled to solidifying point before it strikes the furnace wall. It is possible that some of the spheres referred to may be derived from combustion of coal in this way. The deposit obtained upon the roofs of buildings in cities is very rich in spherical particles ; probably they are carried out of the chimneys and deposited with the sooty matter. A sample of the deposit from the roof of the Meteorological Office, South Kensington, contained spheres up to 42 microns in diameter, some of which were perfectly transparent, like balls of glass ; others were black with a rough surface, while others, again, were amber-coloured and green with polished surfaces.

Origin of the Spherical Particles.—Among the suggested explanations of the origin of spherical particles in the air we may place the following :—

(*a*) Micrococci.
(*b*) Spores of fungi, or pollen grains.
(*c*) Drops of oil or of solution.
(*d*) Furnace ash.
(*e*) Bits of crystal too small to show definite shape.
(*f*) Organic matter synthesised from carbon dioxide and water by radioactivity.
(*g*) Cosmic or solar dust.
(*h*) Volcanic dust.

Considering each of the above separately, we may dismiss most of them as unlikely in the present case.

(*a*) Micrococci should show more uniformity of size than the spheres noted. They should presumably be independent of, or vary inversely with, the smoke content of the air, and should be susceptible to staining. Micrococci are larger than the spheres collected. We could not rely upon them

to explain the sudden increase of numbers in March and subsequent decrease.

(*b*) Spores are rarely less in diameter than 12 microns, and pollen grains than 25 microns. Few of the particles noted exceeded 2 microns. Spores are susceptible to staining and would not increase in March.

(*c*) Drops of oil or solution would be soluble in xylol or water.

(*d*) Smoke from industrial furnaces would not show large variations in the percentage number of spheres on different days, and their comparative absence before March 4th cannot be explained on that hypothesis, unless possibly they were coming from a single localised source, and thus varied with the direction and strength of the wind.

(*e*) Crystals below a critical size appear spherical in shape, and the spheres in the records may be minute crystals of insoluble matter. But they have no effect upon polarised light and show no tendency to grow together. Further, this does not explain the increase in March.

(*f*) Formation of globules of carbohydrates by radio-activity has been described.[1] It would not explain the increase of spherical particles in March or the variation with smoke content of the air.

(*g*) Cosmic dust. This is a possible explanation, but it does not account for great variation from day to day. If the whole of the upper air carried spheres, they should be detected all over the world. This was not noted. Records taken in Portugal in April contained no spheres, nor did others taken at sea.

(*h*) Volcanic dust is a possible source. Particles of material thrown molten into the air would assume a spherical shape and, cooling quickly, would remain structureless. Dust is known to travel great distances, as was noticed at the time of the eruption of Krakatoa in 1883; for some time before March there was great volcanic activity in Europe.

A sample of the finest dust collected near Krakatoa after the eruption of 1883 was examined (*see* Fig. 44). Only the relatively large particles, which had settled near the volcano,

[1] Harrison Glew: *Nature*. 3rd June, 1922, p. 714.

were available, and comparison with the minute spheres obtained in the records of the jet apparatus is hardly justified, though information was obtained which may throw light upon the nature of the material of the spheres. Nearly all the particles consisted of thin flakes of colourless glassy material with a finely pitted surface, broken into irregular angular pieces. The appearance suggested fragments of

Fig. 44.—Volcanic dust from the eruption of Krakatoa, in 1883, collected near the volcano after settling. Magnification, 800 diameters.

thin-walled bubbles blown in molten glass. The size of the pieces ranged up to 18 microns, the average being about 12. Very few were smaller than 3 microns, but there were some spheres of diameter 1·2 microns, identical in appearance with the unknown atmospheric dust. There were also a few perfect spheres with smooth surface about 5 microns in diameter, some appearing reddish-brown in colour.

When mounted in Canada balsam, the large irregular particles disappeared, the refractive index being the same as that of balsam. Their positions could then be dis-

tinguished by the fact that many of the marks on surfaces were really adhering particles, which in balsam stood out as black spheres up to 1·2 microns in diameter. Air bubbles in the balsam were quite different in appearance. Occasionally black spheres up to 3·5 microns in diameter, made more obvious by the disappearance of the irregular pieces, were also seen. Further particulars of these spheres are given in a paper by Dr. Owens before the British Association, 1922, published in the *Journal of the Society of Chemical Industry*, October 31st, 1922.

Formation of Aggregates

Another problem is the aggegation of particles found upon records. It was often noticed that a record showing a uniformly scattered deposit contained here and there a clump of particles, and some evidence was obtained that the number of such clumps or aggregates had a relation to the velocity of air passing through the jet. When the velocity was kept low by drawing out the plunger of the pump slowly, a large number of aggregates was found, but when the plunger was withdrawn sharply the aggregates were either entirely absent or very few. There are many points of interest centering round this question ; for example, did the aggregates exist in the air before it was drawn into the jet, and were they broken down by the high velocity though permitted to pass by the low ? Or, were the particles separate and discrete when suspended in the air, and the aggregates formed during the process of taking the record ?

Again, was the cause of the aggregates, electrical or mechanical ? It is known that particles suspended in the air may be highly electrified ; for example, smuts have been produced in the air of a room which were perhaps 2 mm. or 3 mm. in diameter, but so light that they settled very slowly. On approaching one of these smuts with a stick of sealing wax which had been rubbed to electrify it, the smut first approached the sealing wax, but when it arrived within about $\frac{1}{2}$ inch of the wax it suddenly exploded and was violently repelled in small particles away from the wax. Again, it has been shown experimentally that particles of smoke in the air may have charges of opposite signs.

On examining the transparent spheres already referred to, it was found that, when strong sulphuric acid flowed under the cover-glass, it loosened the attachment of the particles to the cover-glass, and they could then be seen suspended in the acid and undergoing Brownian movement. They soon, however, collected together in clumps, very similar in appearance to the aggregates above referred to. The effect is not produced when water flows under the cover-glass, and possibly sulphur fumes absorbed from the air by the condensed water may have some effect in this direction. Another possible cause is that, in taking a record, a drop of condensed water may strike the cover-glass, and on this drop dust particles may subsequently impinge to collect together in the form of an aggregate. Against this it must be noted that the usual appearance produced by the impact of water droplets upon a record is the formation of clear spaces where the drops strike the already deposited dust.

Shapes of Particles

The particles obtained in the dust counter are of a variety of shapes. The majority are black, irregular and opaque, or semi-opaque, and many appear as spurious discs, being below the limit of resolution of the microscope. Nevertheless, there is a tendency, particularly during a thick smoke fog, for the particles to be rounded or kidney-shaped, with a long diameter of about 2 microns and a short diameter of 1 micron. Some, again, present a dumb-bell appearance, something like diplococci.

Crystals obtained on records are not usually well formed, so that they afford but little help in the identification of the material of which they are composed. Some indication, however, as to the source of the impurity is afforded by the presence or absence of crystals and spherical particles.

Deterioration of Records with Keeping

It has been found that records tend to deteriorate after being kept for a few weeks. The dust becomes obscured by drops of liquid condensed on the cover-glasses, although

the glasses are apparently hermetically sealed at the edges. As the cement used contains no constituent which is volatile at ordinary temperatures, the origin and nature of these drops are not clear, but they seem to be connected with the means employed for cleaning the cover-glass before use. Condensation takes place over the whole surface of the cover-glass, and generally appears independent of the record, but in some cases there is much greater condensation upon the actual dust. Experiments have shown that cleaning the glasses with a handkerchief which has been previously handled promotes rapid condensation, so it is probably due to the presence of minute quantities of hygroscopic salts.

Hygroscopic Nuclei

It appeared probable that, if a haze were due to hygroscopic nuclei causing condensation of water before the air had become super-saturated, as suggested by Aitken, there would result a haze of liquid droplets, or at least of soluble salts surrounded by a coating of liquid, and the behaviour of the droplets in the dust counter should throw light upon their nature.

If, for example, the particles are liquid, then there should be no difference in the number trapped in the jet when the damping chamber is in position, or when the record is taken without it. Records were, therefore, taken in duplicate during a haze and the number of particles on the record with the damping chamber compared with one without it. For example, in the fog of November 13th, in London, two records were taken ; that with the damping chamber showed a much greater number of particles than that taken without. On the other hand, on January 17th, 1923, during a dense fog in London, when similar duplicate records were taken, there was evidence in both of large numbers of water drops having struck the record. In the one for which the damping chamber was in position most of the particles were washed away by the water. The number of particles per cubic centimetre on this occasion was 53,000. It thus appears that liquid drops were present in the air.

On July 22nd records were taken at Cheam, which were

dealt with somewhat differently. The day was dull and overcast; it had been raining all the morning; there was very little wind, and what there was came from the south. There was, however, a heavy haze, spoiling the visibility; it cleared off about an hour after the records were taken. The temperatures were as follows: at 9 a.m., dry bulb, 61·5°; wet bulb, 59·5°; and at 9.45 the dry bulb was 62·5°, and the wet bulb 60·5°. The relative humidity was, therefore, falling, and the conditions were such that the haziness might be regarded as due to drops of water. Two records were taken of 1,000 c.c., numbered 3 and 4. No. 3 was with the damping chamber, and No. 4 without. These were mounted in such a way on microscope slips that the record could be dried in a desiccator, and they were placed in a desiccator for about twenty-six hours and then examined. No. 3 showed a number of dried-up stream beds and dried drops. The record itself consisted of a mass of irregularly shaped particles, most of them evidently insoluble in water, and in the dried-up stream beds and drops were a few crystals, some spindle-shaped and some rhomboids. The record was spread over the surface of the cover-glass for a considerable distance by the condensed water.

Record No. 4 was compact and was not spread like No. 3, thus indicating that there was not much liquid. There were a few crystals similar to those found in No. 3, but most of the particles were irregular dust particles, of a diameter of about 0·8 micron. In both these records there was evidence that, while a certain amount of soluble salts existed, the main part of the suspended matter was insoluble.

On July 11th also, dust records were taken, at Cheam. The weather had been very unsettled and rainy, with clear atmospheres for some weeks and winds between south and west. For three or four days a high-pressure area had been lying to the east and south-east; it covered the whole of England on the morning of the 11th; the wind then was very light between south and east, and a well-marked haze covered the whole country. It was a bright sunny morning, temperature, 58·5° F. Four records were taken between 8.35 a.m. and 9 a.m. G.M.T., two of 100 c.c. each, one

without and one with the damping chamber in position. These were intended for counting. Two other records were taken of 1,000 c.c. each, one with and one without the damping chamber.

The 100 c.c. records were counted, and that taken with the damping chamber gave 920 particles per cubic centimetre, while that taken without gave 460. This seems to show that there was little liquid present and that the haze was due chiefly to solid particles. Further, under the microscope, the particles were irregular in shape, there were only three crystals, and there was no indication of drops.

The 1,000 c.c. records were too dense to count, but there was obviously more dust on that taken with the damping chamber than on the other. Further, on the side of the record of the former lateral streams were shown due to water; this water would have dissolved any hygroscopic salts present, and when it dried, have left crystals. The beds and sides of the streams, however, were covered with particles similar to those found on the record and very few crystals. A few rectangular plates were detected, but most of the particles were clearly insoluble in water.

The 1,000 c.c. record taken without the damping chamber showed a fair number of drops scattered about, each containing what was apparently a crystal in process of formation. There was about 1 drop to every 200 dust particles. A few rectangular crystals similar to those detected in the other record were seen.

Had the haze been composed of liquid, the record taken without the damping chamber should have shown some lateral streams similar to the other but there were none.

It appears evident that certain types of haze are not much concerned with either water or hygroscopic nuclei, but are due simply to suspended dust or smoke particles.

The presence of hygroscopic salts in the air has been shown by numbers of records taken near the sea. Most of the crystals obtained from the suspended matter in the stream beds by the method of warming the damping chamber, described before, are distinctly hygroscopic. One record taken on the south coast of Portugal on a bright sunny day

was found to contain large numbers of crystals of common salt ; a photograph of this is given in the Fig. 45. On other occasions other crystals have been detected in addition.

An attempt was made to ascertain if there was an increase of salts in the air on approaching the sea by taking a series of records in passing down the River Guadiana, in Portugal, but in each case the particles present were so hygroscopic

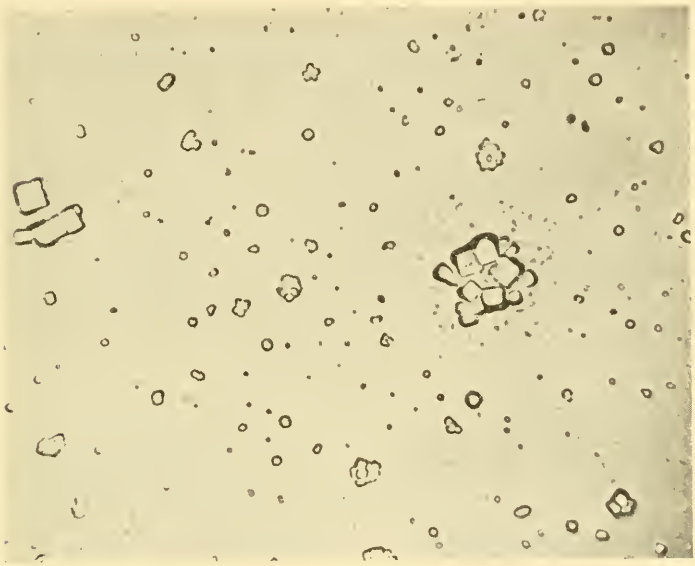

Fig. 45.—Record of suspended matter from the air on coast of Algarve, South of Portugal, during a bluish haze on a hot, sunny day. Magnification, 1,000 diameters.

that condensation occurred on the record, and no comparison was possible.

Hygroscopic crystals have also been found in records taken in the Bay of Biscay, on the coast of Norfolk, and at Flamborough Head, but these have usually taken the form of elongated, needle-shaped crystals. A record taken in the Bay of Biscay during fine weather in April, 1923, contains numbers of colourless needles up to 13 microns in length and 0·9 micron in diameter, together with clear tabular crystals which may possibly have been sodium chloride, although

FIG. 46.—Crystals in a dust record taken from a ship in the Bay of Biscay. Magnification, 2,000 diameters.

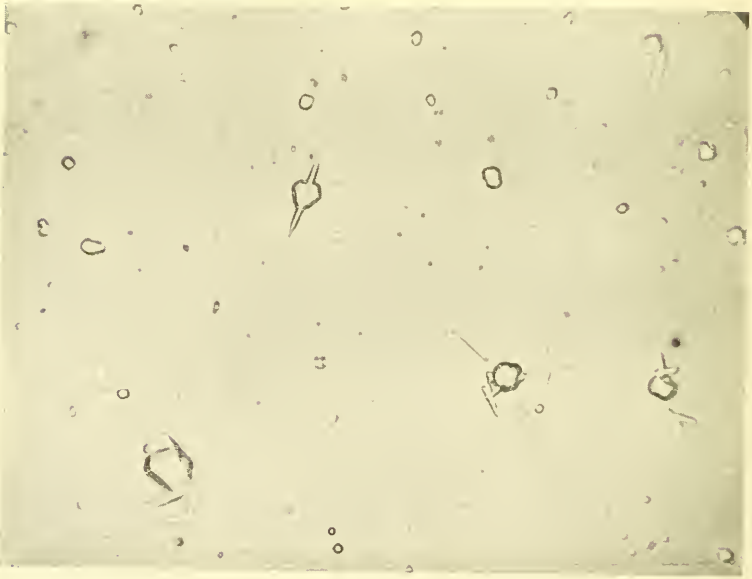

FIG. 47.—Crystals and dust particles in a record taken just outside Vigo Harbour, Spain. Magnification, 1,000 diameters.

they were not perfectly square. The needle-shaped crystals are not sufficiently characteristic to be identified, but they suggest ammonium salts which may have their origin in ships' boiler furnaces. It is possibly no more than a coincidence that at the time of observation a ship was passing on the horizon to windward. A group of crystals in this record is shown in Fig. 46. Another record taken in the Bay of Biscay about the same time showed the presence of dry spherical crystals too small to assume a characteristic shape ; these were most probably sodium chloride. The number of these crystals was counted and the average dimensions ascertained. Assuming them to be composed of sodium chloride of density 2·15, the total amount of salt in this record was of the order of $2{\cdot}68 \times 10^{-8}$ gramme, corresponding with a concentration of 0·0134 mg. per cubic metre of the air. These spherical particles were of a lower refractive index than the glassy spheres usually obtained in smoke records, to which reference is made above.

Comparison of Counts by the Jet Dust Counter with Records of the Automatic Filter

To compare the two methods of measuring suspended impurity, dust records have been taken at short intervals under various conditions, and compared with the results obtained with the automatic filter. The results have been plotted on a curve which is shown in Fig. 48 ; the figures from the automatic filter are plotted as abscissæ against those from the dust counter as ordinates.

The relation does not quite correspond with a straight line. If it did, it would indicate that the relation of the figures of the dust counter to the total quantity of impurity present remained constant for all degrees of impurity. As, however, the figures for the automatic filter are based upon the discoloration of white paper, and, therefore, involve dimensions of the particles as well as number, while the figures from the dust counter take no account of dimensions, a straight line relation would also point towards a tendency to grading of the suspended matter in the air. We should anticipate that the particles being graded by settlement

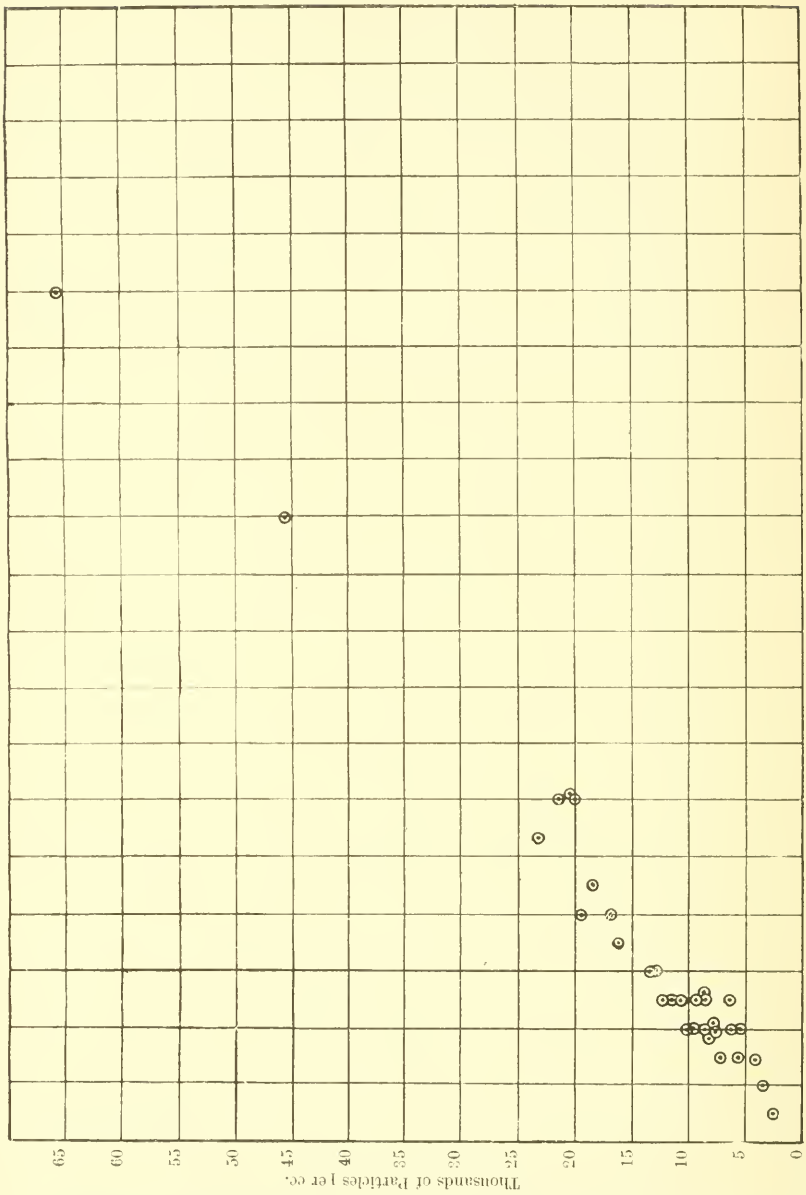

FIG. 48.—In this figure the numbers of dust particles as measured by the jet apparatus are plotted against the shade numbers obtained from the automatic recording filter at the same time and place. Each shade unit corresponds with ·32 mg. of suspended impurity per cubic metre.

those remaining would, in course of time, come to be of approximately the same maximum size. The same phenomenon is observable when water currents or waves operate for long periods on mixtures of different sized particles of stone. The remarkable uniformity of the sand grains upon the seashore is a case in point.

The particles of dust do show a remarkable uniformity in maximum size, with a departure, already referred to in the case of very heavy smoke haze, in which the particles are of distinctly greater diameter than during lighter haze. The difference is due, no doubt, to the rapid accumulation of the impurities and consequent lack of time for grading by settlement. This is confirmed in Fig. 48, in which the graph tends to be convex towards the Y, or dust counter, axis, indicating that at times of heavy impurity the effect on the automatic filter record is relatively greater for a given number of particles than during clearer periods.

With reference to Fig. 48, the graph must obviously pass through the origin, since in clear air no impurity would be indicated by either method of measurement.

When air is drawn through a paper filter, the depth of shade of the record produced increases to a definite maximum, after which the addition of further deposit makes no appreciable increases in the blackness. This maximum is something darker than Shade 20. At the point on the graph representing this unknown shade (Fig. 48) the graph will run vertically, parallel to the Y axis. The last point plotted was obtained from records during a particularly dense haze, that is, the one already referred to, on January 17th, 1923, when the record on the filter was approaching the maximum possible ; this may account for its falling apparently out of line with the other points.

Broadly speaking, the results obtained indicate a reasonably regular relation between the estimates of weight as obtained by the automatic filters and those of numbers by the jet dust counter. This not only suggests that both instruments give a reasonably accurate result, but also contains the indication that the particles suspended in the air are remarkably uniform in their maximum size. The

relation obtained may be expressed by saying that in a city, polluted by smoke, such as London, about 10,000 particles per cubic centimetre correspond to a weight of impurity of 0·8 mg. to 1 mg. per cubic metre.

Electrical State of Suspended Particles

Brownian Movement and Settlement

The suspended particles in the air may be examined while in suspension by the use of dark-ground illumination and of a cell which encloses a small but sufficient volume of air. A low-power objective, about 16 mm., is suitable for the purpose. The cell should be about 3 or 4 mm. deep and 10 mm. in diameter, the upper end being closed by a cover-glass. This cell may be conveniently made by drilling a 1 cm. hole through a piece of flat vulcanite about 3 mm. thick and cementing a cover-glass on one surface. Dark-ground illumination should be very brilliant; if a little tobacco smoke is introduced and the cell is placed upon a microscope slide, the particles of smoke can be seen easily by focussing on to the air inside the cell. All particles appear in such a case as bright points continually moving about with the Brownian movement. This is known to be due to molecular bombardment of the particles, and the necessity for using a low-power objective will be very obvious when the particles are seen dashing about as they do. As a modification the cell may be provided with two copper-plate electrodes disposed parallel to each other inside the cell, and about 2 mm. to 3 mm. apart. These are connected outside to two terminals, which permit of their being charged.

In the cell shown in Fig. 49 a small rubber bulb, such as is used for filling a fountain pen, is fixed on a tube entering one side of the cell, while a similar tube at the other side permits smoke, or the air to be examined, to be drawn into the cell.

With a microscope, suitably illuminated, the suspended particles may be examined under the influence of an electric field. It will then be seen that they sometimes move in different directions, some towards one electrode and some

towards the other, the direction depending upon the sign of their electric charge.

A suitable dark ground for this purpose can be easily obtained by using an Abbe condenser with a wheel stop, or, better still, by the use of a paraboloid. The rate of settlement can be measured in this cell. This observation is conveniently done when a smoke cloud with a large number of particles is in view, by focussing on the floor of the cell and

Fig. 49.—Cell with electrodes for examining charges on the suspended matter in the air.

noting the time required for the last particle to reach the bottom. It may reasonably be assumed that some of the particles were initially close to the roof of the cell, and thus the time required to fall through the distance of 3 mm. between the top and bottom of the cell may be found. Particles of tobacco smoke examined in this way settle at the rate of 0·75 mm. per minute. Such particles are, however, excessively small, probably 0·2 to 0·3 micron, and it can easily be seen that it would not require much vertical movement of the atmosphere to keep particles of this size in suspension.

CHAPTER X

OBSERVATIONS WITH THE JET DUST COUNTER (*continued*)

In this chapter it is proposed to describe some dust records of more than usual interest. Some of these were obtained by Dr. Owens during a journey to Toronto in the summer of 1924 to attend the meeting of the British Association.

Atlantic Records

While crossing the Atlantic the opportunity was taken of testing the air for dust.

Three records were obtained in mid-Atlantic on July 28th ; they were taken at the bow of the ship in order to avoid any dust from the ship, and no dust could be detected on any of them.

A fourth record taken at the same time showed a fair number of crystals of some unrecognisable salt, but no definite dust particles. Another taken at the same time also showed numbers of crystals, not of any characteristic shape and apparently not hygroscopic, and sparingly soluble in water.

There had been a fog, off and on, all day on the 28th, but at time of taking records the weather was clear.

On July 30th there was a slight mist and a light wind from the north-west. Records were taken at 8 a.m., from the bow, and in these a few crystals, probably of common salt, and some yellowish needle-shaped crystals were found, but no dust particles could be recognised.

St. Lawrence Dust

On entering the St. Lawrence the channel south of Anticosti Island was taken ; the wind was light and dead ahead,

and it was a bright sunny day. A haze of some sort, which was suspected to be dust, was visible on the horizon in front. A sample taken showed a few scattered dust particles—about eleven to twelve per cubic centimetre—also some needle-shaped crystals, which were hygroscopic. The dust particles were up to $1\frac{1}{2}$ micron in diameter, but mostly between $\frac{1}{2}$ and 1 micron.

Salt Crystals in the St. Lawrence

On the evening of the same day—July 31st—at 6.30 p.m., very remarkable records were obtained. The sun was shining and a white haze could be seen overlying the water under the lee of the south bank of the St. Lawrence. Samples were taken at the bow of the ship : the sun was straight ahead, and while the haze was very obvious in front and quite white, it was invisible astern. Mr. M. A. Giblett, of the Meteorological Office, who was on board, took a reading with an Assmann psychrometer at 6.30 p.m., and found a dry bulb temperature of 55·3 : wet bulb, 50·8. The air was, therefore, fairly dry, its relative humidity being about 72 per cent.

The records consisted almost entirely of crystals, each lying in a drop of water, or of drops which, on warming, formed crystals. These crystals were highly hygroscopic, and usually were square or rectangular plates ; on warming the drops, crystals of a variety of shapes appeared, some definitely hexagonal, some skeletal.

In one record, of 500 c.c., two organic cells were found, probably moulds. There were very few ordinary dust particles present. It appeared probable that all the crystalline salts that were found in the records were derived from the sea by evaporation of fine spray particles. The crystals were all too small for the application of chemical methods of examination ; the use of polarised light showed that none of them were doubly refracting.

Artificial Salt Crystals

In the hope of throwing some light upon this point, a solution of sea salt was subsequently made and sprayed into

the air of a room. After the visible spray had settled down, records were taken, with the result that a plentiful supply of crystals exactly similar in appearance to those found in the St. Lawrence was obtained. This confirms the suggestion as to their origin.

Salt Crystals and Fogs

The existence of hygroscopic salts in the air in the vicinity of the region where fogs are so prevalent is an interesting feature of the records referred to. It suggests that particles of such salts may be one of the causes of these fogs, as water would begin to condense on them above the dew point, and thus fog might be formed when otherwise—that is to say, in the absence of the hygroscopic particles—it would not occur. In nearly all records taken at sea crystals of salts have been found, while this is not the case inland.

Records on Lake Ontario

While crossing Lake Ontario on August 5th a white haze, very similar in appearance to that seen at the mouth of the St. Lawrence, was observed; but as the sun declined the haze grew darker and a little purple in colour, and the sun set red. It was a warm sunny day with clear sky and a few light clouds. There was not wind enough to ripple the water. Records were taken at 7 p.m. and 8 p.m. from the upper deck of a lake steamer, well clear of the funnel smoke. It turned out that the haze was composed of ordinary dust or smoke particles—about 180 per cubic centimetre—with a few needle-shaped crystals and others. Doubtless the deposit was due to smoke from Toronto and other cities near, as well as that from the lake steamers.

Dust Records in Madrid

During a visit to Madrid in 1924 for the meeting of the International Union of Geodesy and Geophysics dust records were taken; some of them are of considerable interest.

In the Sud-Express on the journey from Paris to Madrid

a record in the carriage showed 13,000 particles per cubic centimetre. It is evident that the air enclosed in railway carriages may be unfairly laden with dust particles. Some of these no doubt are derived from the smoke of the engine, but a large proportion are probably churned up from the cushions and fittings of the carriages.

In Madrid, a city where there is little smoke, it was observed that, although no smoke haze was detected in the streets, yet, when the city was viewed from a hill in the vicinity, a very obvious haze was seen drifting across it down wind, and chiefly derived from the chimney stacks of factories on the outskirts of the city. A series of records were taken from a hotel window in the Paseo del Prado, and the following figures for dust counts were obtained at different times of the day on October 9th, 1924.

	Particles per Cubic Centimetre.
9.20 a.m.	420
Noon	550
3.20 p.m.	149
7.20 p.m.	2,500
10.40 p.m.	1,000

There was thus a minimum about 3 p.m., and a similar minimum was found in records taken on other days. A curious point to be noticed about the records is that those of the early morning showed a large number of spherical transparent particles, about 1 micron in diameter, with a smaller proportion of large irregular particles of 2 to 5 microns. Some of the spherical particles were transparent, others coloured red. As the day wore on the number of spherical particles diminished, while the number of irregular particles increased. In the evening records there were very few spherical ones and a great majority of irregular ones.

From this we may conclude that the morning records were mainly attributable to smoke from the fires which were then being lighted, since this is the most probable origin of the spherical particles ; whereas the evening records are mainly due to dust stirred up by the street traffic. It is possible that the minimum, about 3 to 4 p.m., was due to the Spanish

custom of an afternoon siesta, but the observations were too few for definite conclusions.

Observations during London Fog of December 11th, 1924

Two records were taken on December 11th, during the prevalence of a very dense fog, which covered most of the country and disorganised the traffic. These bring out a point of special interest.

The first was taken at 8.45 a.m., at Cheam, in Surrey, about twelve miles to the south-west of London. The limit of visibility was about 70 yards, and the record obtained from 50 c.c. of air with the dust counter showed a trace indicating a large quantity of water by the numbers of stream beds blown out on the sides of the records. The quantity of dust present was comparatively small, the count amounting to between 4,000 and 5,000 particles per cubic centimetre; the average diameter of the particles was about 0·5 micron. The second record was taken in London at 12 noon on the same day, and showed little or no water, as the dust trace was intact except at one point. There was evidence of some water particles striking, but nothing like so many as on the Cheam record, and no lateral streams were produced except at one end. The number of dust particles present amounted to about 27,000 per cubic centimetre; the diameters of the particles ranged from 2 microns down; a large proportion were over 1 micron.

Apparently, the inference to be drawn from these two records is that, while outside the city at 8.45 a.m. the fog consisted mainly of water with a certain proportion of soot particles, in the city at noon it consisted mainly of soot particles with a small proportion of suspended water drops. From the diameters and numbers of the particles it may be inferred that by weight there was approximately fifty times as much suspended impurity in the London fog as in that at Cheam.

The records were not taken at the same time, but as the fog persisted fairly continuously throughout the day, this

hardly introduced a serious error. The small size of the particles points to the grading effect of settlement ; the larger particles settle out, leaving the smaller to travel onward. It was, indeed, evident that considerable settlement of smoke particles had been going on, because the roads in the neighbourhood of Cheam on the morning of the 11th were covered with a thin oily-looking film, through which footmarks broke, thereby showing up the road material underneath, of quite a different colour.

It is fairly obvious that in the country, as exemplified by Cheam, the fog was mainly composed of condensed water contaminated with some of the smoke drifted from the city ; while in London the water had to a great extent been vaporised by the heat of the city and its place taken by soot.

Observations from other Countries

In response to the request of the International Union for Geodesy and Geophysics, observations have already been received from a number of countries. The officials who have been good enough to interest themselves specially in this inquiry are Mr. Hunt, Director of the Service, and Dr. Edward Kidson, in Australia ; Professor Eginitis, in Greece ; Dr. Anders Ångström, in Sweden ; Dr. Gorczynski, in Poland ; Dr. Marvin, Chief of the Bureau, and Dr. H. H. Kimball, in the United States. From the returns we have extracted the following information as to the maximum and minimum number of " smoke particles " per cubic centimetre in the several localities (see Table, p. 196).

An observation by Dr. Owens, taken on the Atlantic Ocean during a fog in July, 1924, showed that there were no particles of the nature of smoke in the sample. It is, in consequence, of special interest to learn the condition of the atmosphere as regards dust at different heights in the free air over the earth as determined by observations with the dust counter in aeroplanes, balloons, or airships. Observations of this kind have been taken in the United States through the good offices of Dr. H. H. Kimball, who is in charge of the inquiry for the Weather Bureau of the United

Comparison of Dust Counts in Different Countries

Locality.	Duration of Observations.	Smallest Count.	Largest Count.
Athens .	Jan. to April, 1924.	40. Mar. 7 . . .	4,300. Jan. 2. Count only approximate.
London .	Dec., 1924.	300. Very clear day .	60,000. Foggy day.
Melbourne .	April, 1923, to Aug., 1924.	23. Mar. 6. Fine-weather type, clear atmosphere; frequent thunderstorms during previous day.	2,012. April 5. 1924. During April the atmosphere was unusually still, and consequently smoky.
Stocksund . (Small villa town 5 km. north of Stockholm.)	1923.	40 to 120. Oct. 16. Few and uniform particles.	480 to 800. July 5. Visibility 2 to 4 km.
Warsaw .	May to Sept., 1924.	19. May 23. 7 h. Wind S.E. 5.	854. July 8. Wind S.W. 1.
Washington	1923 to 1924.	59. Sept. 21. S.W. 6; raining.	1,785. Nov. 12. Wind S. Visibility, 3 miles.

States. We have noted the following among the observations which have been reported :—

Observations in Aeroplanes

		Particles per Cubic Centimetre.
1923. April 6	At 12,000 feet . .	1,357
,, 28	,, 6,000 ,, . .	158
Aug. 15	,, 10,000 ,, . .	89
,, 16	,, 10,000 ,, . .	48
,, 20	,, 10,000 ,, . .	55
,, 21	,, 9,000 ,, . .	32
,, 24	,, 10,000 ,, . .	59
,, 29	,, 10,000 ,, . .	52
Oct. 25	,, 10,000 ,, . .	43
,, 26	,, 10,000 ,, . .	55
,, 29	,, 10,000 ,, . .	29
,, 30	,, 10,000 ,, . .	31
,, 31	,, 10,000 ,, . .	55
Nov. 2	,, 5,000 ,, . .	75
,, 3	,, 5,000 ,, . .	59

Observations in Balloons

			Particles per Cubic Centimetre.
1924	April 1 (9 h. 30 m. p.m.) .	At 7,000 feet . .	9
	„ 12	„ 4,000 „ . .	59
	„ 18	„ 4,800 „ . .	38

Observations in Dirigible Balloon

1924.	April 28	At 600 feet .	35 ; 117 ; 108

The large range of the number of dust particles in the free air at considerable heights is to be related with the identification of the dust horizon, to which reference was made in Chapter II. When the inquiry is extended over so large a range, the appropriateness of the application of the term "smoke particle" becomes very doubtful. Air-borne particles at great heights are supplied by the dust of deserts during sandstorms and by volcanic eruptions. On such occasions the coarser particles often fall as red rain or dust rain, while the finer particles remain suspended in the atmosphere, and are gradually diffused over the whole earth.

One of the notable instances of red rain is described in a paper by Dr. H. R. Mill and R. G. K. Lempfert before the Royal Meteorological Society.[1] The standard instances of fine dust in the atmosphere are those connected with the eruption of Krakatoa, in 1883, and the eruptions of La Soufrière and Mont Pelée, in 1903.

Dust in the Upper Air

We supplement our account of the use of the jet dust counter with some results for the upper air in addition to those given in the preceding paragraphs. Smoke or dust is normally dispersed in an upward direction as well as laterally and down wind, and it is evident from ordinary observations of dust haze that the upper limit is sometimes very well defined ; with such a haze may sometimes be observed a clearly cut upper surface forming a "dust horizon," below which the air is thick with suspended matter, and above which it is comparatively clear. Investigation into the

[1] "The Great Dustfall of February, 1903, and its Origin," *Q. J. Roy. Met. Soc.*, vol. xxx., p. 57, 1904.

vertical distribution of impurity should throw light upon the causes of the thick smoke haze or fog from which our big cities suffer.

Up to the present very little has been done in England

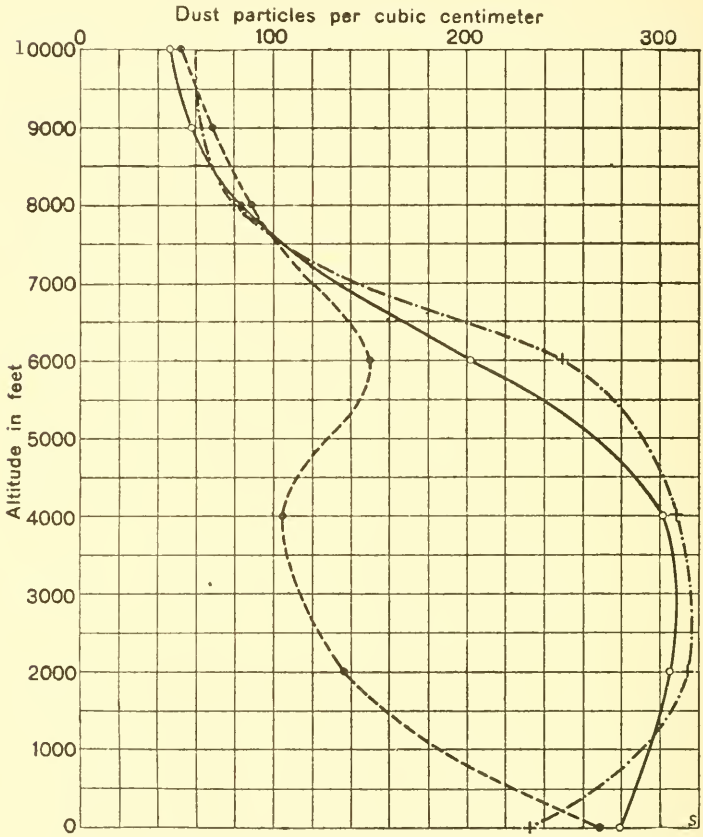

Fig. 50.—Atmospheric dust content determinations during aeroplane flights, August, 1923. o, clear sky a.m.; +, clear sky p.m.; •, cloudy sky after rain.

about the vertical distribution of impurity; but in the United States of America very valuable observations were contributed by Dr. H. H. Kimball and I. F. Hand to the *Monthly Weather Review* of the United States Department of Agriculture in March, 1924. A de Haviland aeroplane

was used and provided with pipes to carry the smoke of the exhaust to the rear of the cockpit occupied by the observer. Ascents were made during August, 1923, and records were usually obtained at 2,000, 4,000, 6,000, 8,000 and 10,000-foot levels.

A curious difficulty was encountered in taking these records, which made it necessary to take them during the ascent only and not during the descent. The metal of the

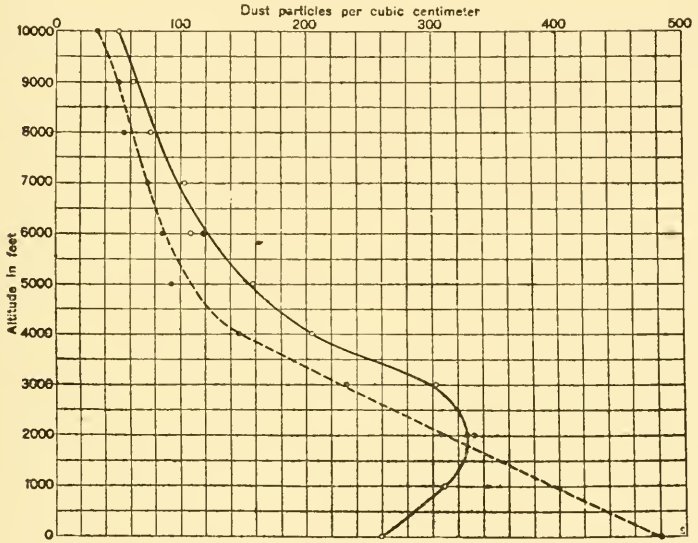

FIG. 51.—Determinations of the dust content of the atmosphere during aeroplane flights, October to November, 1923. o, clear sky a.m., full line ; •, cloudy sky a.m., broken line.

dust counter became cooled during the ascent, and on descending it did not warm up so rapidly as the surrounding air ; in the records taken during the descent the dust was, in consequence, washed away by an excessive condensation of water.

Flights were also made in October and November, 1923, one at a height of 14,000 feet. In the November ascents records were taken at 500-foot intervals.

The mean results obtained for August are plotted in the curve (Fig. 50), and certain conclusions emerge therefrom.

With a clear sky in the morning there was more dust near the ground and less between 2,000 and 7,000 feet than in the afternoon. The increase at high levels as the day goes on is clearly due to convection. The records shown for August 29th followed a rainstorm of the previous night, and showed less impurity. Often with clear skies there was an increase in the dust content with elevation up to about 2,000 or 5,000 feet, and this increase was accompanied by an observable loss of visibility. Thus the observer's note for August 20th stated: "The ground visibility was very good, and objects were seen with distinctness, but above (5,000 feet) the sky appeared to be filled with dense haze."

The results obtained for October and November, 1923, are shown in the curve (Fig. 51). This also brings out the curious difference in distribution under a clear sky and a cloudy one.

Many of the above records were taken by Dr. C. le Roy Meisinger, and it is very much to be regretted that the observations were brought to a sudden end by the untimely death of Dr. Meisinger. He and his pilot, Lieutenant Neely, were making observations in a balloon over Bemont, Illinois, during a thunderstorm; it is believed that the balloon was struck by lightning, as it exploded and burst into flames; both Dr. Meisinger and his pilot were killed.

CHAPTER XI

DUST IN EXPIRED AIR

Tyndall's Experiment

The efficiency of the respiratory passages in removing suspended matter from the air has usually been assumed to be very high, and it has been further assumed that only by coughing, sneezing, speaking, or other explosive effort, are solid particles carried out in the breath. This idea appears to have its basis upon an experiment,[1] which Tyndall

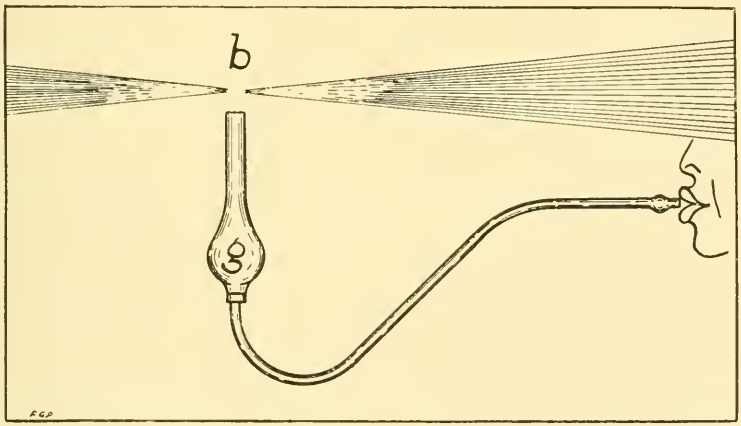

Fig. 52.—John Tyndall's experiment made "prior to 1869."

describes thus: "Condensing in a dark room, and in dusty air, a powerful beam of light, and breathing through a glass tube (the tube actually employed was a lamp glass, rendered warm in a flame to prevent condensation of the breath) across the focus, a diminution of the scattered light was first observed. But towards the end of the expiration the white track of the beam was broken by a perfectly black gap, the

[1] "Floating Matter in the Air," John Tyndall, F.R.S., p. 46. Longmans, Green & Co., 1883.

blackness being due to the total absence from the expired air of any matter competent to scatter light. The experimental arrangement is represented in Fig. 52, where *g* represents the heated lamp glass, and *b* the black gap cut out of the beam at its brightest point. The deeper portions of the lungs were thus proved to be filled with optically pure air, which, as such, had no power to generate the organisms proved by Schwann to be essential to the process of putrefaction." These results appear to the authors to have been often misinterpreted to mean that air expired in the ordinary process of breathing is free from suspended impurities. A study of Tyndall's description of the experiment indicates that what he really found was simply that the air at the end of a forced expiration—that is, the air from the deeper portions of the lungs—was optically pure, as tested.

Tests by Filtering

The methods described in this book, when applied to the same experiment, prove that air expired in the ordinary process of breathing, *i.e.*, tidal air, always contains a large percentage of the suspended dust which enters on inspiration. The air which can be expelled by a forced expiration also contains a certain proportion of the suspended impurities breathed in, the proportion depending chiefly upon the conditions of breathing. There is no suggestion, however, that air in ordinary breathing carries out from the lungs any particles other than those which are inspired.

One method of experimenting was as follows: A standard paper filter for taking single records, as described in Chapter VII, was fitted with a connection by which the air from a small rubber balloon could be aspirated through the paper. The balloon, and all connections, were very carefully washed out, and subsequently filled with the air to be examined.

Some of the tests are given in the Table on p. 204. They show that the expired air contained a considerable amount of dust. It was necessary with this method to use at least 2 litres of air, and thus several expirations were required to fill the balloon sufficiently. The method was not, therefore,

applicable to the last part of the reserve air, as it was found that the presence or absence of dust therein depended on whether or no deep inspirations had been taken shortly before. However, another more delicate method was subsequently used, which supported the conclusions drawn from the filter tests.

Referring to the Table, column 2 gives the impurity in the air as breathed, columns 4 and 6 the quantity and percentage in tidal expired air, while columns 7 and 9 give the same for reserve air. The prominent points are that, while tidal expired air contains a large proportion of the dust inspired, the proportion in the reserve air is usually much lower and very much more variable.

It is curious that an artificial fog of solid black particles, made by burning paper, soaked in a solution of KNO_3, did not appear to penetrate to the deeper parts of the lungs ; the same remark applies to fog made by burning brown paper, in which case the fog was of liquid drops. It is probable the size of particles played an important part.

The very variable percentage of dust found in reserve air indicates that it depends on some variable condition, and, as pointed out later, this was found to be the nature of the breathing before testing, *i.e.*, whether quiet and shallow, or deep.

The actual percentages given in the Table are not to be taken as very accurate ; the only inference it is desired to draw is that dust is present in expired air in appreciable quantities. In all the above tests it is probable that a considerable percentage of the dust adhered to the damp walls of the balloon. The figures can, therefore, be taken as giving minimum quantities only for expired air.

Tests by the Dust Counter

The next tests were made with the jet dust counter.[1]

In each of the cases referred to 50 c.c. of air were used, and tests made in London during a slight smoke haze. These tests were as follows :—

(1) The air of the room as breathed.

[1] *Proc. Roy. Soc. A.*, vol. 101, 1922.

TABLE.—FILTER RECORDS FROM EXPIRED AIR IN LONDON

1	2	3	4	5	6	7	8	9	10	11
Date.	Ordinary Air.		Tidal Expired Air.			Reserve Expired Air.			—	—
—	Shade.	Volume and Remarks.	Shade.	Volume.	Percentage of Dust in Inspired Air.	Shade.	Volume.	Percentage of Dust in Inspired Air.	Experimenter.	Remarks.
1920.										
Mar. 17th	6	2 litres natural smoke fog	4	2 litres	66	—	—	—	J. S. O.	Several expirations required to fill balloon. In all cases breathing was through the nose.
,,	6	,,	—	—	—	3·5	2 litres	60	,,	
1921.										
Oct. 1st	8	,,	1	2 litres	12·5	0	,,	0	G.M.W.	,,
Sept. 29th	12	,,	—	—	—	1	,,	8·3	,,	,,
,,	12	,,	—	—	—	2	,,	16·7	J. S. O.	,,
,,	4	,,	2	2 litres	50	—	—	—	,,	,,
Sept. 28th	11	—	—	—	—	Under 1	2 litres	9	G.M.W.	,,
,,	4	2 litres natural smoke fog	2	2 litres	50	—	—	—	,,	,,
Nov. 7th	10	4 litres natural smoke fog	$3\frac{1}{2}$	4 ,,	35	0·5	4 litres	5	,,	
The following tests were made with artificial fog from smoking paper :—										
Aug. 12th	1	2 litres KNO_3 paper	—	—	—	0	2 litres	0	G.M.W.	Smoke consisted of black solid particles.
,, 15th	$3\frac{1}{2}$	4 ditto	1	4 litres	35	0	3 ,,	0	,,	,,
,, 23rd	4	4 litres brown paper	$1\frac{1}{2}$	,,	37·6	0	4 ,,	0	,,	Smoke consisted of liquid drops.

(2) Expired tidal air, during ordinary quiet breathing.

(3) The last part of the reserve air which could be expelled by forced expiration, after a long period of quiet breathing.

(4) The same as (3), after taking about six deep breaths.

The same tests were repeated by another experimenter to ascertain if there was any personal factor, and at the end of the series a second sample of the air breathed was taken as a control against variation in dust contents. The time required for taking all the above samples of air was one half-hour. The results of these tests are set forth in the accompanying Table, of which the last column but one gives the number of dust particles as a percentage of the number in the air breathed.

EXPERIMENT ON EXPIRED AIR WITH JET DUST COUNTER—LONDON, DECEMBER 6TH, 1921

Volume of air tested was 50 cubic centimetres.

Air Tested.	Number of Dust Particles per Cubic Centimetre.	Percentage of Number in Inspired Air.	Maximum Diameter Particle Microns.
Ordinary air as breathed before test	5,650	—	1·70
Tidal expired air—J. S. O.	4,200	74	0·85
Ditto—G. M. W.	4,000	72	0·85
Last part of reserve air after period of quiet breathing—J. S. O.	400	7	0·85
Ditto—G. M. W.	140	2·5	0·80
Last part of reserve air after deep breathing—J. S. O.	1,180	21	0·85

Referring to this Table, it will be seen that the effect of the air passages in removing fine dust in ordinary quiet breathing is practically negligible, since the expired tidal air contained about 74 per cent. of the dust in the inspired air. The last part of the reserve air, after a long period of quiet breathing, contained very little dust, although it is to be remembered that the period of quiet breathing probably did include a few deep breaths, and possibly coughing, etc.

After taking a few deep breaths, the reserve air was found to contain a large quantity of dust, amounting in one experiment to 21 per cent., and in another to 26 per cent.

It is thus obvious that there is no complete removal of dust from the air in its passage to the deep portions of the lungs, and it seems probable that, when the expired air is dust-free, it is simply owing to long periods of quiet breathing which did not disturb the air in the deep parts of the lungs and allowed the dust particles to settle. Briefly, the purity is due not to filtration or removal of dust by the air passages, but to a settlement in the deeper parts.

A test made of the last part of reserve air, immediately after getting up in the morning, gave 117 particles of dust per cubic centimetre. After a few deep breaths, a second sample gave 2,130, while the air as breathed at the time contained well over 10,000 particles per cubic centimetre.

Another test made in the evening of the same day, after ordinary breathing, but after slight exertion in walking upstairs, gave 585 particles per cubic centimetre, and after taking six deep breaths the number had risen to 865, while the number in the air as breathed was something over 8,000. Both these tests were made in London.

In no instance was the air from the depths of the lungs found to be dust-free, although many records were taken.

The Table gives one set of observations only, as it serves no useful purpose to repeat figures. These are typical of the results obtained in other tests, and may be taken as a fair statement of the facts.

Reference to the Table will show that expired air seldom or never contains particles exceeding 1 micron in diameter. It thus appears that, while the larger particles are removed in the air passages, the smaller ones are practically unaffected.

Repetition of Tyndall's Experiment

As the results obtained from the filter and jet methods of examinations referred to are in conflict with Tyndall's results, it was thought advisable to repeat exactly Tyndall's experiment in the hope of ascertaining whether the black gap referred to—that is, when no visible light was scattered from the beam—really contained air which was dust-free.

Tyndall's experiment was therefore repeated, using for the purpose a powerful beam of light from an arc lamp in a

projection lantern, and a lens in front of the lantern lens to focus the beam. In this way a very intense illumination was obtained at the focus, and the air was seen to be full of dust. The experiment was made in the evening of November 9th, 1921, at a time when there was a marked smoke fog, and again in the evening of the 10th, when the fog was not so dense. In the first experiment a lamp glass was used, and by blowing expired air across the focus a dark gap was produced towards the end of expiration. The particles of dust in the beam were in rapid motion, and it was found that, when the dark gap was produced in the beam passing through the open air and no illuminated particles were visible, particles could still be seen in the beam when it was caused to pass through the lamp glass, the ends being closed so that the movement of the air was very slight, and individual particles could easily be seen moving slowly through the beam. It thus appears that by simply blowing across the beam a dark gap may be made before the air is really dust-free.

Limits of the Optical Method

Theoretical conditions seem also to indicate that there is likely to be a limit to the sensitiveness of the optical method above described, imposed by the degree of sensitiveness of the human eye, and the time required for the growth of the image. The classic researches made by Koenig and Brodhun on the sensitiveness of the eye to light indicate that there is a certain definite minimum percentage change in brightness of a body which can be perceived by the human eye, and a limit depending upon the illumination of body and background, and upon the colour of the light. The percentage change in tone which can be perceived by the human eye is under favourable conditions about $\frac{1}{2}$ per cent., but may in unfavourable conditions be as much as 10 per cent. This percentage change, known as Fechner's Fraction, varies with the individual and with the order of illumination. It is not easy to apply this to determine the maximum degree of sensitiveness possible in recognising the presence of illuminated dust particles, but it is of importance as indicating

that there is a definite low limit to the sensitiveness of the human eye.

The researches, already referred to, made by Koenig and Brodhun showed that the sensitiveness of the eye increased rapidly as the illumination rose to about one-half of a foot-candle; after this there was a further slower increase of sensitiveness to about 3 foot-candles, and illumination beyond this made little increase in the sensitiveness. This is important in the present connection as showing that, when the illumination of an observed body falls below about one-half of a foot-candle, the sensitiveness of the eye is much reduced, and particles of dust so small that their effective illumination falls below this value might easily escape notice.

The fact that the perception of an image on the retina is not instantaneous, but requires a measurable time to reach a maximum, is also important in this connection, since an object which is moving rapidly may not remain in one position sufficiently long to develop a proper image in the retina. For example, supposing the period required to produce the image is one-tenth of a second, and a small body is moving with such a velocity that it travels through a distance greater than its own diameter, or greater than the diameter of the false disc which represents its image, if small enough, in one-tenth of a second, there will not be sufficient exposure to develop a perfect image.

The Brownian movement of dust particles must operate in the same way as movement due to air currents, so as to reduce the effective illumination by distributing it over a larger area.

It seems, therefore, obvious that the ability to see illuminated dust particles must depend upon such conditions as the nature of the particle, including its capacity for reflecting or scattering light, its size, and the intensity of the illumination. For any particular value of illumination it would seem, therefore, that there must be a limit to the size of a particle which can be seen, since, when below about $\frac{1}{2000}$ inch in diameter, each particle appears as a false disc of the same size, *i.e.*, there is no variation in apparent size, and the brightness of this false diffraction disc must, therefore, vary

with the size of the particle. For these reasons it was suspected that it might be possible to prove that air which was apparently dust free when examined by an optical method, might still contain dust particles.

It was suggested by Mr. Watson, who was helping with the experiments, that in the light of the observed effect of motion of the particles upon visibility, if particles were sufficiently small they would develop Brownian movements, which might be effective in making them invisible. It is well known that fine suspended particles, such as tobacco smoke, show very vigorous Brownian movements, and this appears to be a probable explanation. The particles of tobacco smoke would be under half a micron in diameter, and these were observed to be oscillating through a range of at least 17 microns.

The capacity of the air passages leading to the alveoli is such that, during an ordinary tidal inspiration, the air drawn in does not reach the alveoli, and the interchange which takes place between the inspired air and that already in the lungs is mainly by diffusion, with some slight mechanical mixing at the points of contact. Supposing then, for any reason, the alveoli contain suspended matter in the air enclosed, the particles would rapidly settle out of suspension on to the moist walls, where they would stick and remain undisturbed by any movement of the air, and since the imprisoned air is renewed mainly by diffusion, there would be no opportunity for further suspended matter to gain admission. Under such conditions we should expect to find the air of the alveoli, during normal breathing, entirely free from dust, provided a sufficient time had elapsed after a forced inspiration.

This, however, only applies to normal breathing, and in the case of a forced inspiration there would be an opportunity for dust to reach deeper into the lungs. Thus coughing, sneezing or violent exertion, or any other cause which brings about deep inspiration and expiration, would normally result in the entrance of dust to parts of the lungs which could not otherwise be reached. It is unfortunate that it is in dust-laden and foggy air that coughing and sneezing are likely

to occur, owing to the irritation of the dust. There appears, to be no physical reason for assuming a perfect filtration of the air to account for dust-free air in the deep parts of the lungs.

The experiments referred to in this paper show that the dust in tidal air is very slightly reduced, and the deeper the expiration the less dust is found after a period of quiet breathing.

In making a test for dust in reserve air, it is obvious that the expulsion of the reserve air implies a subsequent inspiration, and thus the reserve air, after this inspiration, cannot be regarded as under the same conditions as that of the forced expiration following a long period of normal breathing. It seems probable, also, that the ciliary action of the epithelial lining to the bronchial tubes can only be effective in the removal of dust particles inspired during normal breathing. In other words, if the charge of dust-laden air is drawn in beyond the ciliary lining there is no mechanism for the return of the dust. These circumstances suggest the possibility that it is deep breathing, due to exertion, or following coughing or sneezing, which is responsible for the transport of dust particles to the deeper parts of the lungs.

Reverting now to Tyndall's experiment, and keeping in mind the fact that the air from the deeper parts of the lungs has been shown to contain dust in considerable quantity after deep inspiration, it does not appear possible that the method employed by Tyndall can have been sensitive enough to indicate the presence of dust unless in large quantity. This follows from the fact that it would be humanly impossible to fill a lamp glass, unless of very minute dimensions, with air from the depths of the lungs in one expiration, and as a forced expiration must be followed by a deep inspiration, the reserve air of the next expiration must be dust laden. If, therefore, the method employed did not indicate the presence of this dust, it suggests that it was not sufficiently sensitive.

An important point in this connection is the dimensions of the particles of dust found in expired air. In all cases the particles from the reserve air were extremely small, the

maximum diameter being about 1 micron, whereas the dust in the inspired air contained very large particles. The fact, therefore, that expired air was found to be free from micro-organisms does not prove it to have been free from dust, as the ordinary bacteria are of much larger dimensions than the dust particles referred to.

With regard to the capacity of small particles to penetrate the lining walls of the air passages, it should be noted that the Brownian motion of such particles may materially assist their powers of penetration. Particles of one micron in diameter, when suspended in a liquid, show vigorous Brownian movements, and it is perhaps more than a coincidence that the majority of the small silica particles found in the ash of silicated lungs are under one micron in diameter. This is put forward merely as a suggestion arising from observations of the life-like way in which such small particles as observed under the microscope work their way through the passages left between larger particles.

Summary of Conclusions

1. The air passages do not act efficiently as a filter, except for the removal of very large dust particles.

2. When breathing dust-laden air, it is only after long periods of quiet breathing that the air from the deep parts of the lungs is dust free.

3. When the air from the depths of the lungs is dust free, the freedom is not due to the removal of dust from the air in its passage to the alveoli, but to the settlement of the contained dust in or near the alveoli.

4. Normal quiet breathing may not carry any dust into the deeper parts of the lungs, and such dust as is carried into the air passages can be dealt with and removed by ciliary action.

5. Deep breathing following exertion or coughing, or accompanying sneezing or yawning, or by voluntary action, draws the dust into the deeper parts of the lungs, beyond the ciliated lining of the air passages, and thus beyond the mechanism provided for its removal.

6. It is suggested that, when working in dust-laden air,

it is the deep inspirations, resulting from the above causes, which are responsible for bringing about disease.

7. Nose breathing does not protect against very fine dust.

8. It is doubtful how far exercises involving deep breathing should be recommended to city dwellers under the present conditions, owing to the polluted state of the air.

CHAPTER XII

SETTLEMENT DUST COUNTER

Coarse Dust

In certain circumstances it is advisable to be able to measure the amount of coarse dust suspended in the air at any moment. By coarse dust is meant dust the dimensions of which are so great as to prevent the particles passing through the slot forming the jet in the dust counter already described. A case in point is the measurement of dust produced in stations where grain is unloaded, where the continual movement of the grain by elevators, etc., causes thick clouds of dust to be suspended in the air. Dr. Middleton, H.M. Medical Inspector of Factories, noticed that such dust contains pointed spicules of 0·3 mm. to 0·7 mm. in length by about 0·02 mm. thick at the base, and ending in points, evidently awns or hairs broken from the grain. As there was no available means of getting an accurate measurement of dust of this kind, the instrument to be described was devised, the object being to get an accurate count of the number of such particles in the air at any moment and, if necessary, to grade them according to dimensions.

The same method may be used for counting bacteria.

The ordinary method of exposure of a plate or dish for a given time, while giving a roughly comparative result, has little value as a quantitative method, since the amount of dust deposited upon a plate exposed in the open depends upon many variable factors, such as size of the particles, their density, the temperature and the degree of turbulence of the air ; all these are unknown, while, in addition, the deposit is obtained from an unknown volume of air. The instrument to be described was designed to eliminate these uncertainties.

A Settlement Dust Counter

The instrument depends upon the principle of enclosing a definite volume of air to be tested in a small vessel with suitable precautions, the height of the vessel being known. The dust in a column of air of this height is allowed to settle upon the surface of a cover-glass, on which it is subsequently counted. The area of the base and the height of the column being known, the amount of dust per unit volume of air can be calculated.

For the measurement of bacteria the instrument is of such design that it admits of being easily sterilised by heating.

The instrument, shown in Fig. 53, consists of a heavy platform or bed plate A, on the upper surface of which a cylindrical air vessel G, open at both ends, is placed. An annular ring is formed in the upper surface of this bed plate to receive the lower end of the cylindrical air vessel. A loose cap H is also provided for closing the upper end of the vessel.

Referring to the air vessel, G, it will be observed that this is a plain open-ended metal tube. It is made in this form intentionally to permit it to be easily filled with the air to be tested by sweeping it axially through such air, and so that vessels of different height may be used if desired.

The diameter of the air vessel is made very large compared with that of the cover-glass, with the object of eliminating any effect which might be produced by the sides of the vessel.

Situated centrally under the axis of the air vessel is a circular hole penetrating the bed plate, which permits dust which settles from the air to pass through it on to a microscope cover-glass placed beneath the hole, as subsequently described. The under surface of the bed plate has a circular recess formed therein, eccentric to the axial hole. The recess receives a drum C, pivoted at its centre to the bed plate by a pivot B, and held in position by a knurled nut F. Capstan arms D project around the circumference, by which the drum can be revolved round its spindle. A stop J is provided, which serves to limit the rotation of the

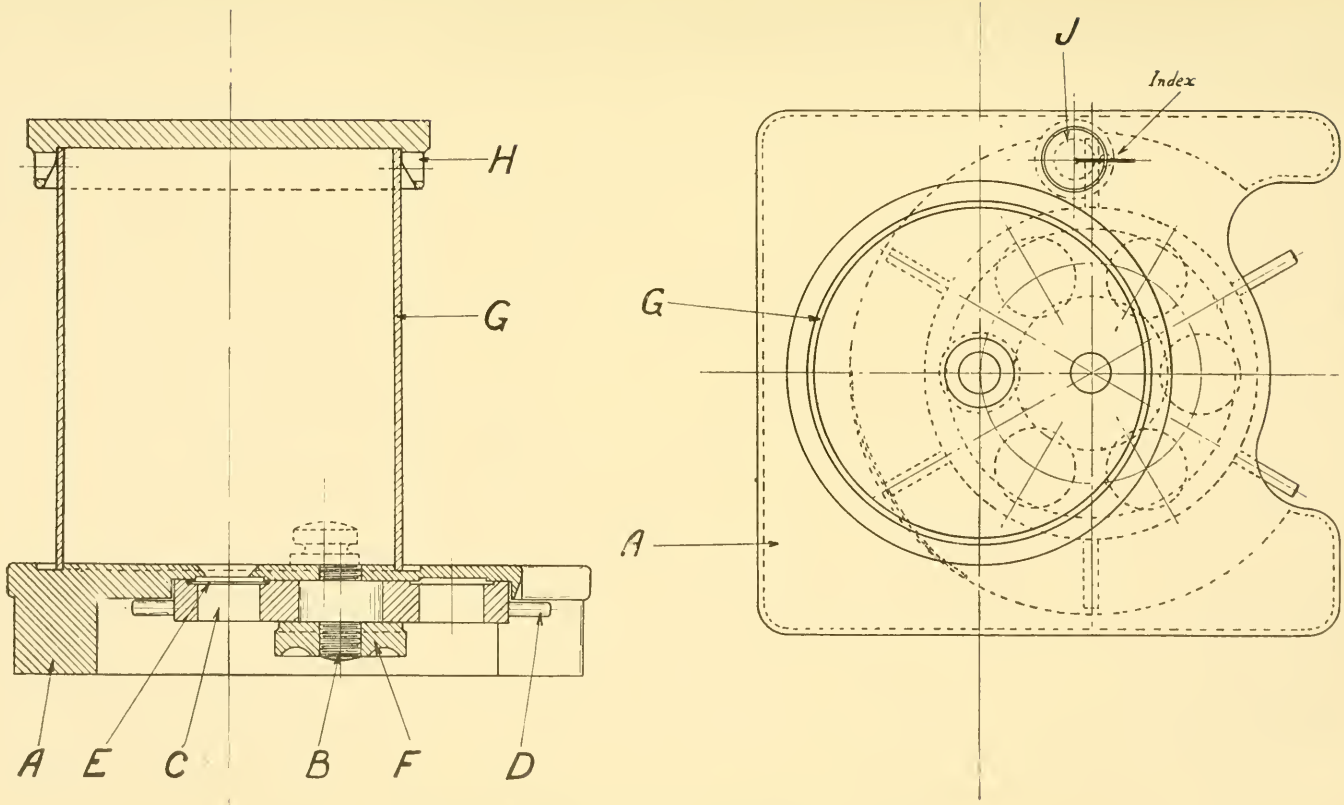

FIG. 53 (A).—Section and plan of settlement dust counter.

drum. The drum has six equidistant holes, and the upper part is recessed to receive cover-glasses. The holes lie in a circle concentric with the drum, and the number of capstan arms projecting from the drum is equal to the number of

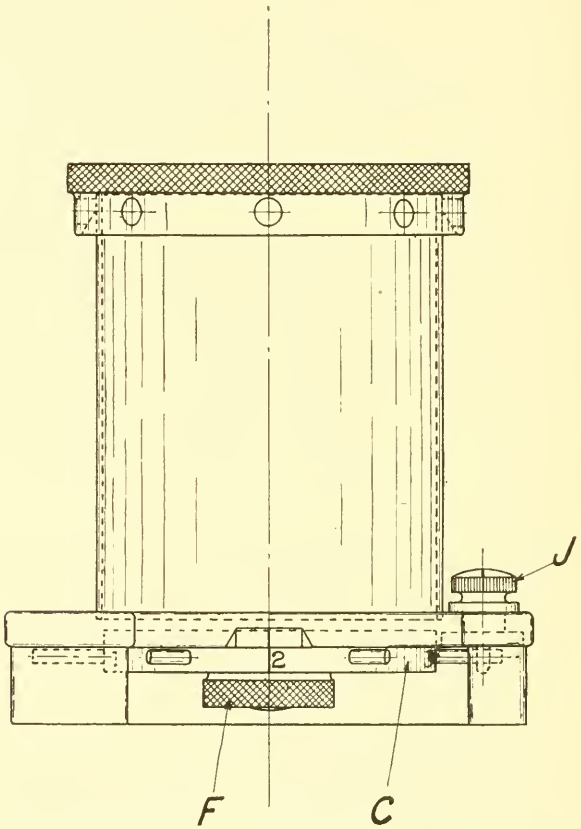

Fig. 53 (B).—Elevation of the settlement dust counter shown in Fig. 53 (A).

holes and recesses. Thus, as shown in Fig. 53 (A), there are six holes, with six recesses for cover-glasses, and consequently there are also six capstan arms. The stop J is so disposed that, when one of the arms engages it, a hole with its recess will be centrally under the axial hole in the bed plate under the middle of the air vessel. An annular recess is formed on the under side of the bed plate above the holes

and recesses, the edges of which hold the cover-glasses in position ; index numbers on the side of the bed plate indicate the number of the cover-glass appearing under the air vessel.

The object of the design is to enable a representative sample of air to be enclosed in the air vessel, and subsequently to permit of the simultaneous closing of the top of the air vessel and exposure of the cover-glass. The need for simultaneously closing the top and exposing the cover-glass arises from the fact that, immediately the cap is placed upon the top of the vessel, the air is imprisoned, and since settlement is going on all the time, any interval between the closing of the top of the vessel and the exposure of the cover-glass would introduce error. It will be noted that surrounding the rim of the cap are series of open holes ; the function of these holes is to prevent the imprisonment of excess air during the process of placing the cap in position upon the air vessel. If any excess air were thus imprisoned, it would escape partly through the hole exposing the cover-glass, and might cause a deposition of dust during its passage. There is very little probability of such an effect occurring with the arrangement shown.

Method of Using the Instrument

The instrument may be used in two ways. The first is intended to provide a means for grading the dust, that is, for ascertaining the time required for settlement of the different-sized particles, and also the numbers of each grade. This is necessary in order to ascertain the time of exposure to settlement which is required to obtain a true record of the amount of dust of any particular size or shape. To use the instrument in this way, five of the recesses in the drum are provided with clean cover-glasses ; the sixth is left empty, and when the drum is replaced the empty hole is put under the air chamber. The air vessel is removed and the instrument placed in the air to be tested. The air vessel is next swept axially through the air and placed upon the bed plate in its annular recess. The stop J is next adjusted by making a complete revolution of the knurled head in a

counter-clockwise direction. This moves the stop to the other side of the capstan arm, which is pushed slightly forward in the process. The drum is then free to revolve when required, and so to expose a cover-glass ; the cap H, which has been placed mouth downwards to prevent contamination with dust, is now placed upon the top of the air vessel, while simultaneously the drum is revolved to bring cover-glass No. 1 in position under the air vessel. The stop J is again moved so that cover-glass No. 2 may be brought into position when necessary, and after a measured interval has elapsed cover-glass No. 2 is brought rapidly into position ; the same process is repeated for the glasses Nos. 3 to 5, the interval for settlement depending upon the nature of the dust. On removal of the drum, the five cover-glasses will have upon them the portions of the dust which settled in the successive intervals. Thus, by examination of these records, the time required for settlement of the dust under investigation may be found.

Having ascertained the proper time of exposure, the required records may then be taken as follows. Three cover-glasses are placed in their recesses in the revolving drum, leaving three alternate holes without any cover-glasses, each cover-glass being thoroughly cleaned before being placed in position. The drum is replaced in the bed plate, the knurled nut F screwed home, and the stop J so adjusted that a hole in the drum comes under the hole in the bed plate in the axis of the air vessel. The instrument is then taken into the air to be sampled and, the bed plate having been placed on a suitable bench or support, the air vessel is removed ; the bed plate is waved through the air to fill the cell at the bottom of the air chamber with the air to be tested, after which the air vessel is passed two or three times axially through the air and brought down on to the annular recess on the top of the bed plate. The stop J is next revolved through a complete revolution in a counter-clockwise direction ; the revolving drum is thus caused to move slightly, and the stop pin to shift to the opposite side of the capstan arm with which it was in engagement ; thus the drum is left free to revolve when required. The cap for closing the top of the cylinder

is next taken in one hand and placed upon the top of the air vessel, while simultaneously the revolving drum is moved by the finger of the other hand until brought up by the contact of one of the capstan arms against the stop. This brings a cover-glass under the hole in the top of the bed plate, and after a suitable interval for settlement, depending upon the nature of the dust being sampled, has been allowed to elapse, the drum is again revolved so as to bring the exposed cover-glass under the shelter of the bed plate. The test may be repeated, using a second or third cover-glass if so desired, after which the instrument is removed to clean air, the revolving drum taken out, and the cover-glasses mounted.

If the dust record obtained is too scattered, it may be repeated as often as desired, using the same cover-glass, or a higher air chamber may be used instead if there is one available.

When the air vessel, having been filled with the air to be tested, is placed upon the bed plate, settlement of the dust commences, but as the top of the air chamber is open no error is introduced in the dust count, since dust which settles out at the bottom, by falling through the open hole in the revolving drum, is replaced by a corresponding amount of dust, which settles into the open upper end of the air vessel. It is only when the vessel is closed by the cap H that settlement inside becomes important, and to avoid error then, as already pointed out, the closing of the vessel and the exposure of the cover-glass must be simultaneous.

Method of Mounting the Records

In order to make the records permanent, it is necessary to treat the cover-glass before exposure so that the deposited dust will adhere thereto. For this purpose a very weak solution of Canada balsam in xylol is prepared, containing approximately 2 per cent. of Canada balsam. The cover-glass, having been thoroughly cleaned, is taken in a forceps, and dipped in the solution: if so desired one half may be kept dry. The cover-glass is lifted slowly from the liquid so as to allow all excess to flow away from the glass,

and allowed to dry ; it dries in a few seconds, leaving an excessively thin continuous film of hard balsam on the part of the surface which was immersed. A sufficient number of cover-glasses are prepared in this way and kept in the dust-proof receptacle provided with the instrument. After taking a record, the drum containing the cover-glass is removed and placed under a glass cover, the roof of which has a disc of white blotting paper, previously moistened by the addition of a few drops of xylol. In a few seconds the film of Canada balsam on the cover-glass is softened by the xylol vapour, and the dust particles adhere firmly. On removal of the cover the balsam rehardens in a few seconds, when the records may be removed and mounted upon slides prepared with tin rings coated with adhesive, such as are employed in mounting the records of the jet dust counter. It has been found that cover slips on which dust is deposited without any adhesive discharge their dust very easily ; the cleaning of the glasses electrifies the surface, and on touching the cover-glass to mount it the dust is sometimes driven off and all deposited on the bottom of the cell. The dust cannot be mounted in Canada balsam in the ordinary way, since the particles become detached from the glass and lose their relative positions, so that it becomes impossible to count the record. Moreover, many of the particles, being practically transparent, almost disappear when immersed in Canada balsam. The portion of the cover-slip left uncoated with balsam permits the particles to be examined dry, if so desired. The cover-glasses having been mounted in position on their cells, the film of balsam on the upper surface may be removed before examination by wiping with a cloth damped with xylol.

For examination of the particles and for counting, a low-power objective, such as $\frac{2}{3}$ inch, may be used, and it is advantageous to use dark ground illumination. A square-ruled micrometer eyepiece, having $\frac{1}{2}$ mm. squares, such as is used in connection with the jet records, is calibrated by means of a stage micrometer, so that the area covered by the squares is known. The number of particles on the record is then counted inside a definite number of squares,

from which figure the number per unit volume can be ascertained.

Care must be taken that the instrument itself is kept free from dust, that is, it must be cleaned carefully. It is intended for use in dusty air where coarse dust particles are settling rapidly, and, therefore, it will soon become coated with dust, and it should be carefully cleaned after use and before being replaced in its box.

The cover-glasses which have been previously prepared with balsam must be protected from dust while they are being placed in the instrument; should dust settle upon them, it may be removed by using a clean camel's-hair brush or blowing upon the surface, but it is preferable never to attempt to place clean cover-glasses in position in very dusty air.

Results Obtained

The following results, obtained by the use of the settlement dust counter, are given by permission of Dr. E. L. Middleton, H.M. Medical Inspector of Factories. The investigation was carried out by him in connection with dust produced at grain-discharging stations.

The grain—wheat, barley or oats—produces dust which contains sharp-pointed hair-like cells, which appear to be a source of great irritation when breathed. In the case of wheat the hairs are collected together in a little bunch, which millers call the "brush," at the apex of the grain. Each hair is from 0·5 to 1 mm. long, is sharp and spike-like in appearance, and consists of a single cell. The base of the hair is about 0·02 mm. in diameter, and contains an air cavity.

The hairs from barley and oats are somewhat similar. Dust from wheat appears to be more irritating to the respiratory passage than that of other kinds of grain.

A few of the results obtained by Dr. Middleton are given in the accompanying table, from which it will be seen that the number of hairs referred to is very considerable, reaching in one instance to nearly 4,000 in 500 c.c. of air, which a man may breathe in a full breath. In the Table there are separate columns for complete hairs and for the broken points.

TABLE SHOWING RESULTS OF TWELVE DETERMINATIONS OF GRAIN DUST

Sample Number.	Where taken.	Grain.	Number of hairs in 500 c.c.	Number of broken points in 500 c.c.	Remarks.
1	Granary—conveyor tunnel .	Wheat.	2,050	—	No. 1 Northern Manitoba wheat.
2	Ship-hold	Wheat.	950	—	
3	Ship-hold	Barley.	2 650	—	
4	Ship-hold	Wheat.	308	492	
5	Ship-hold	Barley.	260	390	Near air duct.
6	Ship-hold (same) . .	Barley.	823	127	Away from air duct.
7	Ship-hold (same) . .	Barley.	1,040	260	Near bucket elevator.
8	Granary—clearing-out bins .	Mixed.	1,261	189	A specially dusty occupation.
9	Granary—sacking wheat at mechanical weighing machine.	Wheat.	187	563	Very little obvious dust.
10	Ship-hold	Wheat.	3,307	573	Wheat from Philadelphia; bucket elevator, very dusty and irritating, very confined hold.
11	Shed on dockside under conveyor.	Barley.	128	637	Very little fine dust—removed by wind and air currents.
12	Hopper weigh cabin . .	Barley.	508	317	Barley from Calcutta; rather dusty and irritating, but modified by wind

CHAPTER XIII

SMOKE MEASUREMENT

It is sufficiently obvious that, if the quantity of smoke emitted from particular chimneys is to be controlled, some means of measurement must be adopted.

The present position with regard to measurement or estimation of smoke is unsatisfactory. Nothing is settled or agreed upon generally, and each sanitary authority or other body interested uses any method that commends itself, without regard to what is being done elsewhere. Thus there is much confusion. The absence of any recognised and generally adopted method for measurement, and the corresponding lack of any standard of smoke emission having some approach to accuracy, have a profound effect upon the problem of smoke prevention. It is possible at present for any one accused of emitting too much smoke to dispute the question with every hope of success, since there is no definition of what is too much.

Before discussing the problem more fully and considering in more detail the methods of smoke measurement already adopted, it may be pointed out that the finding of a method of smoke measurement, which implies also the fixing of a basis for a standard of emission, should not be left to individual effort. The question is important for the country generally, and its solution should not be left to the chance of some individual being sufficiently interested to tackle the problem. It is a problem capable of solution if a properly directed effort be made, but in the authors' view, such an effort should be made under Government auspices. It would involve considerable expenditure of time and effort in experiment and trial.

The emission of dense smoke from furnaces consuming bituminous coal is unnecessary during steady working, and

indicative of waste of fuel and bad furnace construction, or bad working. It is true that there are a few special cases, such as furnaces for heating brewery vats and pottery kilns, where the emission of dense smoke for short periods is still considered essential by some authorities, but it is open to question if this opinion is justifiable. At the same time, it should be remembered that the total absence of all smoke is, in practice, usually impossible of attainment when the economy of manufacturing processes requires the burning of bituminous fuel. An illustration of the difficulty of avoiding all smoke is provided by the large electric generating stations, where unforeseen variations of load occur, such as the increase due to a London fog, with its accompanying demand for artificial light. In such a case it may be necessary to fire fresh boilers very rapidly, and there is no known furnace which will admit of the smokeless combustion of bituminous coal until the temperature of the combustion chamber has attained a sufficient height. Even in steady working it is practically impossible to avoid all smoke, and a faint brown smoke is regarded as indicating more efficient working of boiler furnaces than none at all. The emission of some smoke may, therefore, be regarded as inevitable.

The Legal Position

The present position, therefore, is this. We know that dense smoke is unnecessary, and that entire absence of smoke is at the present time impossible of attainment, but we have not yet settled what should be allowed as a fair and reasonable amount of smoke, having regard to the improved methods of combustion which are now at the disposal of manufacturers.

The Public Health Act of 1875 supplies the present standard by which smoke is judged throughout the country, except in the case of a few important cities possessing special powers on the subject. In this Act it is stated that : " Any chimney not being the chimney of a private dwelling-house sending forth black smoke in such quantity as to be a nuisance shall be deemed to be a nuisance liable to be dealt

with summarily under the Act." Here, then, we have the present standard ; not only must the smoke be black, but it must be a nuisance as well.

There is an alternative method provided by the Act under which proceedings can be taken in respect of fireplaces or furnaces in connection with factories which do not " as far as practicable consume the smoke arising from the combustible used therein." In practice, however, it has been found that this method of abating smoke is unworkable, owing to the lack of some standard defining the meaning of the words " as far as practicable."

The standard " black smoke in such quantity as to be a nuisance " takes cognisance of two separate things in relation to smoke : its quality, that is, it must be black, and its amount, that is, enough to cause a nuisance ; but while account is taken of these two essentials, it is done in such a way as to make it very difficult to prove in any particular case either that the smoke was black or that it was in sufficient quantity to be a nuisance. The point to observe is that the two essentials, kind and quantity, form part of the standard.

Since the date of the Public Health Act of 1875 sufficient improvements have been made in the burning of bituminous coal to call for a reconsideration of the present standard, and the adoption of one which is more up-to-date and which will conform in a reasonable way with the possibilities of modern practice. It is unnecessary to deal at length with the evils attending the emission of smoke from the point of view of the public. They have already (Chapter IV.) been discussed in detail, but it may do no harm to point out again that millions are condemned to breathe the smoke-polluted air of cities, useful energy and money have to be expended in cleaning away soot, buildings are injured and blackened, the daylight and sunshine are cut off, and in many other ways harm is done which, to a great extent, might be avoided if we had a sound, legally enforced standard of smoke emission, based on the known results which the proper application of modern methods of combustion give. Manufacturers might then use the best methods of combustion and the most

suitable appliances. The loss to the manufacturer in soot, estimated as a percentage of his fuel bill, is probably not more than about $\frac{1}{4}$ to 1 per cent., and this is not great enough to prompt much effort to save it. On the other hand, the loss to the public due to the injuries inflicted by smoke is certainly many times greater: hence it is more to the interest of the public than of the manufacturer that smoke should be reduced.

The Need of a Standard Measure of Smoke

One difficulty which has always existed is that of dealing with large and small fuel consumers by means of a single standard, and this has militated against the establishment of a more rational standard than that laid down in the Public Health Act. Clearly we cannot limit a large manufacturer to the emission of the same total quantity of soot as a small one. His furnaces might be better designed and combustion more perfect than in the case of the smaller consumer, but the total quantity of soot emitted might be much greater. Such a limitation would, therefore, work unfairly against the large fuel consumer.

At first sight it would seem that the total quantity of soot emitted by any chimney would be the soundest thing to limit, since it determines the amount of pollution of the air by soot from a particular source; but on closer examination we see that this is not really the best basis. What we are concerned with is the total pollution of the air by the soot of all the chimneys in any particular neighbourhood. For example, the erection of an electric generating station where large quantities of fuel are burnt may, by displacing small consumers who had previously to generate their own power, cause a great reduction in the amount of soot poured into the air. At the same time, the total quantity of soot emitted from such a station might be many times greater than that previously emitted by any one of the smaller power units which it displaced, in spite of the fact that the combustion might be better and the amount of soot per ton of fuel burnt much less.

What we may ask for is that the best and most nearly

smokeless methods of combustion should be used. If we could, therefore, fix a sound standard which would be some measure of the efficiency of the methods and appliances used from the present point of view, it would work no hardship against the large fuel consumer.

We come, then, to the conclusion that what is wanted is a standard of efficiency of combustion from the point of view of the prevention of smoke. This must clearly take into account the amount of fuel burnt, and, if we could measure it, the proportion of the fuel passing out of the chimney as soot would be the ideal standard.

It is the aim of engineers to provide a definite quantity of air for each pound of coal burnt, hence the amount of soot per unit volume of flue gases would vary approximately as the amount of soot per unit weight of fuel, when the air supply is regulated to suit the amount of fuel burnt. In such cases the measurement of smoke density alone would be a sound basis for comparison as to efficiency of combustion. It would also be a fair standard to fix, since, so far as soot is concerned, it would measure the polluting power of the smoke emitted.

It is, therefore, suggested that the word "black" in the present standard should be altered to "smoke of a density exceeding" some fixed standard. The standard should, however, also include a time of emission, and the form suggested is "smoke which exceeds a certain density (as measured in a way to be determined), and which is emitted for a period exceeding so many minutes per hour."

Present Method of Measurement

We have now arrived at a stage at which we can consider the methods which have been in use up to the present. They fall into two broad categories. In one no effort is made at exact estimation, the aim is simply to make a comparison with some arbitrary standard of shade or colour, the smoke being viewed as it escapes from the top of the chimney. The second includes attempts to measure accurately the proportion of the fuel wasted in smoke.

Shade Charts

In the first group the intensity of the shade of the smoke is compared with what is usually termed a smoke scale, of different degrees of darkness, either printed on a white background or in the form of smoked or neutral-tinted glasses.

Brief reference will now be made to some of the scales and instruments which have been tried.

The Manchester Smoke Abatement Committee of 1881 used a scale of ten shades of grey.

The English Smoke Abatement Committee of 1895 used four shades on their scale.

In the Paris smoke tests of 1897 five shades were used; the apparent densities were plotted on a rotating drum at half-minute intervals, giving a curve, the area enclosed by which was taken as a measure of the density of the smoke.

The Prussian Commission of 1894 used an elaborate photometric method, comparing with a scale the varying intensity of a ray of artificial light which passed across the smoke between the boiler and the chimney.

The Ringlemann smoke scale has six shades, numbered 0 to 5; the charts are made by ruling black lines on a white background, two sets being ruled at right-angles. This scale must be viewed from a distance of about 50 feet, and its use requires two persons to make an observation, one to hold the cards, which are very large, and one to compare them with the smoke. The shades are obtained by ruling lines of different thickness as follows:—

No. 0 is white.
No. 1 has black lines, 1 mm. thick and 9 mm. apart.
No. 2 has black lines, 2·3 mm. thick and 7·7 mm. apart.
No. 3 has black lines, 3·7 mm. thick and 6·3 mm. apart.
No. 4 has black lines, 5·5 mm. thick and 4·5 mm. apart.
No. 5 is black.

Bryan Donkin's scale, like the last, has six shades, 0 to 5, and white to black. They are of the same intensity as the Ringlemann shades, but of a uniform grey colour, so as to be viewed from close at hand.

The Coal Smoke Abatement Society, London, has adopted

a scale of four shades : pale grey, grey, black, and dense black. With this and the last there is always some difficulty in printing, as it is hard to repeat with certainty exactly the same shades. Also, there is a tendency for the shades to fade with time, and to take on a yellowish tint. The Society has tried many ways to overcome this difficulty.

The Public Health Department of the Corporation of London adopts a scale of nine shades of grey, from white to black.

Photographic methods of measuring the shade of smoke have been tried, but without any conspicuous success. A photograph sometimes gives a very false impression of the colour of smoke ; in fact, it has been shown that a chimney which has no smoke issuing from it, but only a stream of hot gases, will sometimes come out in a photograph with all the appearance of a dense volume of smoke blowing away from the top.

Instruments for Measuring Smoke

Among instruments designed for smoke measurement, the following may be mentioned :—

An American instrument which uses a disc containing neutral-tinted glasses or smoked celluloid of different shades, each glass having a central hole. The disc rotates on the end of a tube, and the smoke is observed through a hole in the smoked glass ; the disc is moved until a shade is found which corresponds with the smoke.

Lovibond's tintometer consists of a tube having within it a diaphragm in which are two $\frac{1}{8}$-inch holes $\frac{1}{2}$ inch apart ; the smoke is observed through one hole, and slips of neutral-tint glass are placed in grooves opposite the other until a correspondence in shade with the smoke is obtained. In this the glass is observed by the medium of light reflected from a slip of matted white opal inclined at an angle in front of it, so as to obtain a uniform background. In both this and the instrument previously described nothing is attempted beyond matching the smoke in shade or colour.

In an instrument which Dr. Owens has devised five neutral-tint glasses are fixed in a revolving disc on the

end of a tube, and numbered in the order of their density from 20 to 100. The smoke is examined through a central hole $\frac{1}{8}$ inch diameter, and matched with one of the glasses by revolving the disc. On the body of the tube are numbers giving the observed density divided by the diameter of the chimney, and thus the true relative density of the smoke ; or, if so calibrated, the weight of soot present per unit volume of flue gases can be computed.

There are considerable possibilities of error in all these instruments. Dr. Owens' is an attempt to advance the matter a little by allowing for the thickness of the layer of smoke looked through.

The mere comparison of the blackness of smoke by eye with an arbitrary scale does not give satisfactory results, the greatest fault being that chimneys are compared without reference to their diameters. There is also much room for error from the personal factor, smoke appearing of different shades to different observers. Again, the presence of wind, the direction of the line of vision relative to the smoke column, the colour of the background, all influence the result. In the American instrument and in that of Dr. Owens the errors due to the background are eliminated as far as possible, as the smoke and shaded glasses are viewed against the same background. In comparisons with a paper scale, the smoke is viewed chiefly by transmitted and the scale by reflected light. This is a great source of error ; the background of the smoke varies, that of the scale being fixed ; while for true comparison both smoke and scale should be looked at by transmitted light and against the same background.

Fig. 54 illustrates another instrument designed by Dr. Owens to meet the requirements. It was called the carboscope, and was made by Messrs. B. J. Hall & Co., Westminster. As it attains some way towards the object sought, a somewhat more detailed description may be of interest.

The instrument is in the form of a small telescope, having in the optical system, at a point which may be brought into the focus of both object glass and eyepiece, a revolving disc, eccentric to the axis of the telescope and containing a number

of graduated smoked glasses arranged in cells around its axis. The glasses fill only half of each cell, so that by revolving the disc, as each cell with its glass is brought successively into the axis of the telescope, the smoke may be viewed through the open half of the cell and matched to the glass in the other half. The smoked glasses are numbered in the ratio of their thicknesses, *e.g.*, glass numbered 20 is equivalent in transmission value to twenty unit thicknesses of the unit shade chosen. No. 40 is equivalent to forty thicknesses, and so on.

Unit density is taken to be that of smoke which in a layer, 20 feet thick, transmits 80 per cent. of the light falling

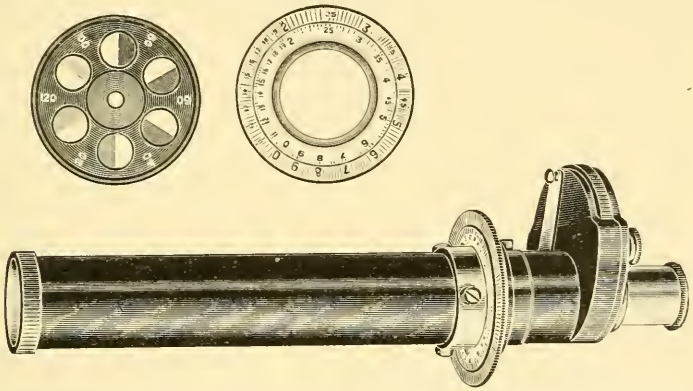

Fig. 54.—The Carboscope, for the measurement of smoke by inspection.

on it. If a smoked glass No. 20, equivalent to twenty layers of unit thickness, also transmits 80 per cent. of the incident light, then unit density may also be defined as :— Smoke of which a layer or column of unit thickness, say, 1 foot, matches a smoked glass of unit density or thickness. Thus, a layer N feet thick of smoke of unit density will match a glass of N units thick ; and generally, if D represents the thickness of a smoke column, and N the number of unit thicknesses of smoked glass required to give a match to it in shade, the density will be equal to N/D units, as above defined. This unit is an arbitrary one, and it is in these units that the instrument measures density, and thus enables the observer to compare chimneys of different diameter.

After measuring the weight of soot per unit volume in smoke of unit density, the readings of the instrument may be converted into weight of soot per unit volume of smoky air by simply multiplying the reading of the instrument by the weight per unit volume of soot in smoke of unit density.

Gravimetric Methods

Turning now to absolute measurement, many attempts have been made to determine the percentage of the weight of the fuel which is lost in soot, but they are characterised by remarkable want of agreement between the results. The method commonly used is to aspirate a measured volume of the flue gases through a filter, of asbestos or cotton wool, and to weigh the actual matter trapped or the carbon dioxide produced on burning the filtrate.

Other methods are the precipitation of the soot by means of low-pressure steam or by static electricity, or the flue is swept out before and the soot weighed after burning a fire for a certain time; this latter method takes no account of the soot escaping into the air.

The chief objection to filtration lies in the fact that one cannot be sure of getting a representative sample of flue gas so far as soot is concerned.

Scheurer-Kestner, adopting this method, concluded that $\frac{1}{2}$ to 1 per cent. of the fuel in boiler furnaces was lost in smoke.

In one case by the filtration method, Professor C. Roberts, at the Manchester Smoke Abatement Exhibition in 1882, according to the published figures, got more soot than there was coal burnt. In another case the soot was 40 per cent. of the fuel.

Professor Cohen, in testing open house-fires at Leeds, got about 5 per cent. of the weight of the fuel in soot.

It is not necessary to cite other instances, as these will show the differences in the estimates of soot which have been obtained.

Much appears to depend on the direction and shape of the inlet to the filter, and the velocity of the gases entering. The position in the chimney is also of importance, both as

regards distance from the fire and the part of the cross-section from which the gases are drawn. If too near the fire the soot will not be mixed properly with the flue gases; if at the top of the chimney, there will probably be unequal distribution of the soot also, owing to the greater velocity of the gases at the centre than at the sides; also, the soot adhering to the sides is neglected.

Conditions to be Fulfilled

Any method of smoke measurement, to be of use, should fulfil certain conditions, and these may be summarised as follows:—

(*a*) It should give a reasonably exact measurement of the things which it is desired to know.

(*b*) The personal factor should be eliminated so far as possible, otherwise observations by one person will not compare with those by another.

(*c*) The method must be capable of easy use by a stoker in charge of the furnace, so that he can keep the smoke under observation and ascertain when a definite limit is being passed.

(*d*) It must be capable of easy use by inspectors.

(*e*) There must be no vagueness or uncertainty about the result.

When we contrast the standards now adopted with the ideal which we have set forth, it will be seen that there are very radical differences.

As regards the word "black," the standard now embodied in the Public Health Acts, it may be stated with certainty that there is no such thing as black smoke, when the word is taken in its literal meaning. Again, there are many kinds of coloured smokes—yellow, greenish, brown, and almost white—all of which may be as injurious as the so-called black smoke. If the word is not to be taken in its literal meaning, then it has no definite meaning at all and becomes a mere matter of opinion. Suppose, again, that smoke appears to an observer who looks at it against a bright background to be black. Another observer, examining the smoke from the opposite direction, may find it of a

different colour; one sees it by reflected and the other by transmitted light. It is not necessary to labour the point further; such a word can have no place in the definition of a standard of smoke emission.

Let us look, then, at the second part of the legal definition, that is, "in sufficient quantity to be a nuisance." What is there definite about this, and who is to decide whether the smoke is a nuisance or not? A single smut, if it lodges in the reader's eye, may be a very real nuisance, but this would hardly be taken as sufficient ground in a court of law to justify the enforcement of penalties.

There is another aspect of this provision as to nuisance which does not receive the attention it deserves. It implies that smoke nuisance is capable of being located definitely to a particular chimney. As a matter of fact, we know that a very real nuisance to millions of people results from the accumulated smoke of numbers of chimneys during a so-called smoke fog. It cannot be denied that here there is smoke in sufficient quantity to be a nuisance, but it is not due to any particular chimney, and, therefore, cannot be dealt with under the Act. It is intolerable that civilised human beings should have to suffer from such preventable pollution of their atmosphere as is now experienced in some of our large cities.

It is useless to approach this question from the point of view of economy to the smoke producer; it is, perhaps, unfortunate that the amount of soot emitted even in dense smoke is so small in comparison with the weight of fuel consumed that it pays the furnace owner better to retain plant, though it is out of date, than make the necessary modifications required to prevent the emission of undue smoke.

The actual amount of fuel lost in smoke cannot be very great relative to that burnt, although in the aggregate it is important, and amounts to many thousands of tons per annum in London alone.

Professor Roberts, in his Manchester experiments of 1882, by sweeping out the flue of an open fire, obtained 2·25 per cent. of the weight of the fuel as soot, and in other cases

from 0·05 to 0·5 per cent., so that the total amount produced must be much greater than this.

A continental lampblack factory recovers as lampblack only 3·3 per cent. of the weight of the coal burnt; but, although as much smoke as possible is produced for the purpose of making lampblack, it is of the sooty, as distinct from the tarry, variety, and it is the latter which plays the most important part in smoke from ordinary fires. We must not, therefore, regard 3·3 per cent. of the fuel as the maximum amount of smoke obtainable.

General Summary

The rational method of approaching the problem of smoke prevention appears to be as follows :—

First obtain a method of measuring smoke which will fulfil the required conditions as set forth above. Next ascertain for the different industries what amount of smoke might be fixed as a reasonable maximum, having regard to all the conditions of the industry and the present state of science as it bears upon combustion. The amount of smoke should be ascertained by use of the method of measurement referred to.

If these two conditions are fulfilled, the next step—that of altering the law so as to enforce the keeping of smoke below the standard fixed—would be comparatively easy, and could not be objected to on any reasonable basis.

Summarising what has been said as to the method of measurement most likely to satisfy the necessary conditions, for simplicity it appears advisable that some optical means should be adopted. Methods involving filtering and weighing, or estimation in some other way after filtration, are liable to be so complicated as to be of little use as a standard method. The same applies to precipitation by spray or the use of electricity, either of which could with suitable elaboration be made to give the desired information. The optical methods are more promising, and since there are many objections to examining the smoke as it issues from the top of a chimney, we naturally conclude that it would be better to examine it near the base of the chimney. Rough approximate methods involving the examination of the smoke

through peepholes in the flue or chimney have been used with fairly good results, but to give measurements which are of real value for comparison with other chimneys many precautions are required. One advantage of these methods would be that the stoker could keep the smoke under observation easily. It would, however, have the drawback that a smoke inspector might not be very welcome if he wished to examine the smoke at the base of the chimney. It would seem necessary, therefore, that some reasonably accurate method of measuring from the outside by looking at the top of the chimney should be used, at least as an approximation. Thereby an inspector would be enabled to judge whether a chimney appeared to be emitting smoke beyond the allowed limit. This method need not be of great accuracy, and might be used rather as an indicator, so that, when, *primâ facie*, there was evidence that the limit had been reached, the inspector might be authorised to examine the smoke in a more accurate way. Therefore in each factory chimney some permanent means of examination should be installed convenient for examination by the stoker and available, when necessary, for the use of the smoke inspector.

CHAPTER XIV

THE REMEDY—THE GENERAL PROBLEM

The problem of preventing smoke is very difficult in a country in which the main supply of fuel consists of smoky bituminous coal. It is evident that we may attempt a solution in different ways, but, owing to the fact that no great sources of natural energy, such as waterfalls or rapid rivers, are available in the British Isles, we must, for the present at least, look to the combustion of fuel in some form for the energy required for industrial purposes, and for warming and cooking in our houses.

The problem naturally falls into two broad divisions :—

(*a*) The discovery of a practicable means of preventing smoke while utilising bituminous coal.

(*b*) The adoption of administrative measures necessary to assure or encourage the application of the method or methods when found.

In the present chapter it is proposed to deal with the first of these divisions, that is, the search for a practical remedy, and, further, we shall confine our attention to the domestic smoke problem.

We may aim either at providing a fuel which will burn without smoke, or at using the ordinary bituminous coal in such a way as to prevent smoke formation, or we may combine these two methods.

The smokeless fuels now available for domestic use are gas, coke, and anthracite, and a somewhat uncertain but small amount of semi-coke, by which we mean coal that has been subjected to carbonisation at a low temperature. Although electricity cannot, strictly speaking, be called a fuel, its use for domestic heating and cooking may also be considered here.

Gas Fires

The gas fire is, of course, smokeless, and would, if it replaced coal fires, entirely eliminate domestic smoke.

Great improvements have been made in recent years, and it is now possible to obtain gas fires which, with proper provision for ventilation, are free from all objection on the score of unduly drying the air or vitiating it. The amount of heat radiated by a good gas fire may be as much as 50 per cent of the total heat of the gas burnt, and it is now well recognised that heating by radiation is the most healthful method. Besides its radiated heat, a well-appointed gas fire may give 20 to 25 per cent. as convected heat.

The remaining objection to the use of a gas fire for warming is, perhaps, its monotonous uniformity. There may be something more than sentiment in the attractiveness of a coal fire : the very fact that it is alternately bright and dull, with a large gradation of brightness and dullness, may make it more acceptable to the human subject than a uniformity which provides in the aggregate the same amount of heat. Warming by radiation from a fire is almost as attractive an occupation as sunning oneself in the open air, but one soon gets tired even of sunshine, and one can form some conception of what is meant by travellers in tropical countries when they write of the sun as the enemy, or by the Oriental proverb : "Out of God's blessing into the warm sun." There is already an automatic change in the intensity of a gas fire when the evening pressure comes on, and perhaps in time some further departure from monotonous uniformity may be devised.

There are many gas fires in use which are objectionable owing to inefficiency and insufficient provision for carrying off the products of combustion. These are chiefly survivals of past years.

Owing to the cost of gas it is necessary to economise the heat : hence small flues are used. Also, the absence of smoke during combustion makes it possible to use flues without having them choked with soot. A small flue can, therefore, be used for gas, and is often so used in order to reduce the

loss of heat which results from the use of large chimneys, such as those necessary for coal fires. It must not be forgotten, however, that the ventilating effect is not so great as with the larger chimney; hence there is some danger, when using gas fires, that sufficient provision may not be made for ventilation.

The type of gas fire which is without any flue is not to be recommended. There are possibly a few positions, such as in draughty halls, where they might be used without great danger, but the absence of a flue to carry away the products of combustion makes the flueless gas fire a form to be avoided except in very special circumstances.

There are two points which call for special reference in connection with the use of gas fires. It has been stated that the burning of gas would not prevent the vitiation of the air by sulphur, since the gas itself contains sulphur. To get an idea of the amount of sulphuric acid added to the air by burning gas a few figures should be useful. Coal gas may contain 30 or 40 grains of sulphur per 100 cubic feet, and its calorific value is about 500 B.Th.U. per cubic foot. Coal, on the other hand, has a calorific value of 13,000 B.Th.U. per pound, and it contains a varying percentage of sulphur—2 per cent. is not far wrong as an average. From these figures it is easy to calculate the amount of sulphur which is burnt by the two methods and goes to vitiate the air. For example, if we burn enough gas to produce the same amount of heat as would be given by 1 lb. of coal the amount of sulphur burnt in the gas will be 8 grains, and in the coal 140 grains. Thus the substitution of gas for coal would go far towards eliminating the sulphur impurities in the air.

Another objection which has been raised to gas for domestic heating and cooking is its cost, and in discussing the cost reference may be made to the table given on p. 247, in which the costs of heating by different methods are compared for certain fixed prices of fuel and—a very important point—for continuous working. The gas cooker is never called upon to do continuous work, and the gas fire, in the majority of cases, is also only used when required. It is possible to work in this way with gas, because it is

immediately available when required ; the gas fire gives its full amount of heat a few minutes after lighting, whereas a coal fire does not develop its full heat for an hour or two ; when the fire is not required, the gas can be turned off, but the coal fire cannot be extinguished. Thus the figure of cost for continuous working is modified in practice owing to this possibility.

There is a further advantage of gas over coal in that no store of fuel and no coal cellar are required, nor is there the production of dust and ash, nor the labour of carrying coal about—a highly important advantage. On the other hand, the householder who has a store of coal or oil in his cellar has a very gratifying feeling of independence during the wars and rumours of wars that are common occurrences in these days in the industrial world. To induce him to surrender that position requires some assurance. No one can complain if the householder is inclined to act on the principle that smoky coal is better than no gas.

Reverting to the question of ventilation, it has been indicated that, in order to economise heat, the flues of gas fires are kept small. This results in the reduction of the ventilation of the room when compared with coal fires, and provision should be made for an adequate supply of fresh air ; open windows are a convenient way of doing it if the occupant of the room can choose his own position. It is also advisable to see that a free entrance for air to the chimney is provided around, or independent of, the flue drawing the products of combustion from the fire. This is provided for in the modern " ventilating " gas fires by an air entrance under the canopy ; it may be got equally well by arranging the fire so as not to block up the entrance to the chimney, and thus allowing it to induce a draught apart from that passing up its own flue.

A slight digression may be made here with advantage. The subject of heating of houses has been, and is at present, considered far too much from the point of view of economy of fuel or, which is the same thing, the technical efficiency of the heating apparatus, while insufficient attention is given to the subject of ventilation. Ventilation is regarded very

often as a separate problem from heating, but that is quite a mistake ; the method of heating has a profound effect upon the supply of air to a room or a building.

The most efficient ventilator is the open window combined with the ordinary open fire and its large chimney and strong draught. It does not matter what is burnt in the fire from the point of view of ventilation, provided the heat is generated ; it will in turn generate a draught in the chimney. Apart from the draught produced by the fire, a chimney of a large section is practically always acting to draw the air out of the house ; in fact, it only ceases so to act when there is no wind. The wind, blowing across the top of the chimney, draws the air up, and, as has been shown by definite measurements, the draught so produced may be so great that the lighting of a fire in the chimney does little to augment it. The great point to keep in mind is that the heating and ventilating of houses should be inseparable, and the general principle may be laid down that any method of heating which does not itself produce a ventilating effect should be looked on with suspicion. There is one very good reason for this suspicion, and it arises from the desire to economise fuel or its equivalent, so that when a method of heating is installed, such as electric radiators or the so-called radiators operated by steam or hot water, there is a great tendency to cut down the ventilation to a minimum in order to conserve the heated air and avoid having to spend fuel or current upon heating fresh air. The fire, whether of gas or solid fuel, provided with a suitable flue will look after the ventilation if an adequate inlet for fresh air is provided, since the draught up the chimney implies that fresh air is drawn in to supply its place. Failing any special provision, the air is drawn through crevices and casual openings. It is, therefore, important that the users of the room should see that the air drawn in by the fires does not come from a vitiated source, such as from another room or part of the building where the air is impure. In most London houses the crevices of the windows or doors and the cold flues of fireplaces without fires act as the chief inlets for the supply of air. An open window provides an inlet at once so ample and so satis-

factory that its advantages in that respect will be recognised by all who are familiar with them.

The Open Coal Fire

The open coal grate is one of the most important sources of smoke, and there is no grate at present in existence which will burn smoky coal without the production of smoke. There are many advantages possessed by the open grate ; it is cheerful and bright, and provides occupation in attending to it and poking. Its heat is mainly given by radiation, which is the best form ; the temperature of the air itself is not unduly raised, nor is the air unduly dried. Besides these, there is the advantage, already pointed out, that an open fire is an excellent ventilator.

It may be observed, however, that several of these advantages are also to be obtained when a smokeless solid fuel is burnt, such as coke carbonised at low temperature, and, indeed, as shown in the table given on p. 245, the percentage of the heat of the fuel given to the room is greater when low-temperature coke is used than with coal ; the difference in favour of this fuel is about 10 per cent. The ordinary grate, burning smoky coal, radiates about 20 to 25 per cent. of the heat of the fuel into the room. There are, of course, many kinds of domestic fire grates, but there is little difference between most of them as smoke producers so long as the ordinary smoky household coal is used. There is a type of grate in which, after lighting, the draught is caused to pass downwards through the fire instead of upwards, and by this means smoke can be greatly reduced when reasonable care is used. The gases and tar formed when fresh coal is put on the fire are thus caused to pass down through the incandescent part of the fuel, where they have a better chance of being burnt than when allowed to escape from the top into the cold air. But if domestic grates, with their advantages, are to be retained and smoke avoided, the chief hope lies in the use of a smokeless solid fuel, and the only fuels of this kind available are ordinary gas coke low-temperature coke, and anthracite.

Gas Coke

Gas coke is not a very pleasant fuel to burn ; it usually contains an excessively high percentage of ash, and also practically the same proportion of sulphur as the original coal, while at the same time it does not light easily, and burns in an open grate as a dull heavy fire. Hence it is not to be expected that its use will become serviceable in reducing smoke, although a very interesting account has recently been given by Professor C. V. Boys, F.R.S., of a method which he has adopted for burning coke, and which he states gives every satisfaction. This is described in an article in the *Daily Mail* of November 11th, 1924. Briefly, he burns the coke on a plain brick or firebrick hearth, without any grate or any metal in contact with it, and with no draught through the fire except that which enters through the interstices in the sides of the heap of coke. A detailed description of this fire is also given in a pamphlet by the London Coke Committee.

Low-Temperature Coke

Much has been written in the public Press recently about schemes for the production of a smokeless fuel produced in quantity by carbonisation of coal at low temperature, and more particularly about schemes which are being adopted in Glasgow and Nottingham. While from our present point of view any fuels of this type are suitable for domestic use, if not made from coal with too high an ash content, one of the great difficulties in making such a fuel on a commercial scale has been in finding a market for the by-products. There have also been practical difficulties in finding suitable retorts for carrying on the process.

The question of low-temperature coke is discussed more fully in a later chapter, but here it should be mentioned that such fuels do not necessarily contain less sulphur than the same weight of the coal from which they are made. Hence little advantage would be gained from the point of view of removing the sulphur impurity in the air.

Anthracite

The use of anthracite would do away with smoke, but it cannot be looked to for a solution, since there is not sufficient anthracite available. The total quantity produced in England during the year 1923 was about 4,000,000 tons, whereas the amount of coal consumed in domestic fires alone was about 40,000,000 tons. It is evident, therefore, that there is not enough to go round.

That is no reason, however, for not using it where it is available, and there are certain advantages besides smokelessness attending its use. It is found that a closed slow-combustion stove provides the most satisfactory method for burning anthracite. It is very economical, does not require lighting afresh each day, but may be kept burning, with the result that the house is dry and warm night and day through the whole winter. It requires very little attention, and produces much less dust than do the open fires. Owing to the fact that the heating is chiefly by convection rather than radiation, the air of the room is liable to get very warm and dry, while, as a consequence of the reduced draught necessary for slow combustion, the ventilation produced by the stoves is negligible unless they are installed, in the manner already referred to under gas fires, so as to induce a draught through the chimney apart from that which goes through the stove itself. This plan is not usual with anthracite stoves, possibly because it is essential that there should always be a strong pull upon the air coming through the fuel; it has the objection, already referred to, that some of the heat is lost, or at least it is lost to the room, although it is utilised in ventilating. The only objection from the practical point of view to anthracite stoves being set in such a way that a good draught is induced up the chimney is that an adequate flow of air through the fuel must be maintained; subject to that condition, the room may be ventilated just as well as by means of an open fire. Anthracite stoves require care in operation, more particularly because, owing to the reduced air supply, carbon monoxide gas is produced in the stove, and this is highly poisonous and must not be allowed to

escape into the room. Such stoves can be used with gas coke as a fuel, but it is not, as a rule, satisfactory, owing to the high proportion of ash which the coke contains.

Efficiency

The following table of efficiencies of appliances for domestic heating in respect of radiation is taken from the Report No. 3 of the Fuel Research Board[1] :—

Radiation Efficiency : Percentage of Total Heat of Fuel passed into the Room as Radiation

	Percentage.
Ordinary open coal fire—old-fashioned type	24
Open coal fire—barless type	20
Coke fires in barless grate	24½
Coal in same grate	21
Coke fires in a register grate	28½
Coal fires in same grate	24
Low temperature carbonisation cokes	31 & 34
Coal in same grate	24
Anthracite in open grate	27
Coal in same grate	24

The word " efficiency " is often used in connection with the comparison of different domestic fires, and there is a good deal of misconception about it. In the technical sense in which it is used, the " efficiency " of an apparatus or machine means the ratio of the useful work done to the energy put into the machine. Thus, if 100 units of energy are put into a machine—the handle of a winch, for example—and only 70 units appear as useful work in, say, hoisting a weight, the efficiency is 70 per cent. The point to be observed here is that, in order to specify the efficiency, the work which a machine is required to do must be definitely understood.

In the case of a domestic fire, apart from cooking appliances, it is necessary to define clearly what is the function of the fire, and this is usually taken to be the delivery of heat into a room. In this sense heat radiated is included as well as that delivered by convection currents and by conduction to the room, and when it is clearly understood that

[1] Fuel Research Board: Special Report No. 3. " The Coal Fire," by Margaret Fishenden, D.Sc. H.M. Stationery Office.

the meaning is thus limited, no harm is done by using the word "efficiency"; it would be defined as the percentage fraction of the total heat of the fuel which is delivered to the room. This is not, however, necessarily a measure of the value of the fire, since it is based on the artificial definition of efficiency referred to; the real function of a fire is to make the occupants of a room comfortable, and to do this they have to be kept warm, but that is not the whole story. A certain percentage of heat which is regarded as lost is really doing useful work in producing air-flow without which the fire would not burn. Again, the limitation of our point of view to the room alone leaves out of account the rest of the building. For example, the rooms overhead are kept warm by heat entering through the walls of the flue and through the ceilings, and this is also useful work. Again, the walls are being kept dry, and the house habitable, by heat which might from another point of view be considered wasted.

A fire also fulfils a useful function by its appearance alone if it thereby adds to the comfort of people sitting round it.

However efficient a fire may be in throwing heat into a room when it has become well established, it may be of little use if the heat is not available when required. This is often the case when one has to wait a long time after lighting in order to obtain from a fire the necessary warmth. For example, if persons have to spend an hour only in a room, a coal fire lighted on their entrance would be of little use, whereas a gas fire or electric radiator would be giving off its full heat a few minutes after starting.

It is evident, therefore, that we must keep a clear view of the limited value of "efficiency," used in its strictly technical sense, when applied to domestic fires. We may take an example of, say, a coal fire which has been lighted in a cold building with very tall chimneys. The efficiency relative to the room in which the fire is may be measured at 20 or 30 per cent., but relative to the whole building it may be double this amount; in fact, it may approach 100 per cent. We may consider that the only heat lost is that which passes out from the house through the flue, and this is doing useful

and necessary work in maintaining air-flow ; hence even that cannot be strictly regarded as lost. There is, of course, a loss of heat through the walls and windows as well as through the chimney, but it is to compensate for these losses that the fire is wanted.

We must not, therefore, take too limited a view of the function of a fire. It is quite different from the case of steam boilers, where the function of the fire is strictly limited to one thing alone, that is, to produce steam ; and, applied to this case, the word " efficiency " can be used without fear of misunderstanding, whereas in the case of domestic fires the position is entirely different, and when using the word " efficiency " a clear conception should be formed of the limitations of its meaning.

A table from the same report shows the relative costs of the different methods of heating for continuous working.

Table of Relative Cost of Different Methods of Heating Rooms

Method of Heating.	Source of Heat. *For Continuous Working.*	Cost in pence of 100,000 B.Th.U. (*a*)	Percentage heat entering room. (*b*)	Relative Cost. (*c*)
Open coal fire (bad design).	Coal at 52*s.* per ton ; calorific value 13,500 B.Th.U.	2·06	20	1
Open coal fire (good design).	,, ,,	2·06	35	0·57
Closed anthracite stove	Anthracite at 89*s.* 6*d.* per ton ; calorific value 14,000 B.Th.U.	3·43	75	0·44
Hot-water radiators .	Coke at 46*s.* per ton ; calorific value 12,000 B.Th.U.	2·06	75	0·27
Open gas fire (inferior design), continuous work.	Gas at 3*s.* 7*d.* per 1,000 cubic feet, or 8·6*d.* per therm of 100,000 B.Th.U.	8·60	50	1·67
Open gas fire (best design), continuous work.	,, ,,	8·60	65	1·28
Electric radiator .	Electricity at 2*d.* per unit .	58·82	100	5·70

Note.—The relative costs (column (*c*)) are based on the prices and calorific values shown and compared with a coal fire as unit. The figures are given by the expression :—$(c) = 9{\cdot}7\ (a)/(b)$

With regard to domestic appliances for cooking and for heating water, a valuable set of tests has been made by Professor A. H. Barker and embodied in a report of the Fuel Research Board.[1] The tests were intended to bring out the efficiencies usually attained by the ordinary methods of cooking and of heating water in private houses. Certain general conclusions were arrived at, which are set out below. In all cases the efficiencies given are the ratios of the heat which is used for the particular purpose to the total heat of the fuel consumed. A study of these figures will show what a wasteful business the cooking of food and heating of water in domestic houses usually is.

Oven.—The ordinary kitchen range oven was found to give an efficiency which varied from 0·75 to 5 per cent.; the usual value was about 2 per cent. The nominal maximum efficiency of ranges actually on the market varied from 4 to 22 per cent., but the latter figure was only reached after special alterations had been introduced in the existing range which made it practically unusable. It was found that an oven of special design could be constructed to give an actual efficiency of 9·3 per cent. and a theoretical maximum of 23·7 per cent.

Hot-Water Supply.—The efficiency of the apparatus in ordinary kitchen ranges for the supply of hot water varied from 7 to 17 per cent., the usual figure being 11 per cent. In no case did the figure exceed 20 per cent., except in that of an expensive type of specially-designed boiler, where values up to 40 and 50 per cent. were secured.

Hot-Plate.—With ordinary hot-plates attached to a kitchen range the efficiencies varied from 1 to 12 per cent., the usual figure being 4 per cent., while in only a few cases did it exceed 6 per cent.

Combined Efficiency.—The general total efficiency of the whole range, reckoned on the theoretical maximum basis, when used with the oven damper open and the hot-water damper closed, varied from about 5 to 20 per cent., the usual value being 11 per cent.

The general conclusion arrived at was that, apart from its use in warming the house, the ordinary type of modern kitchen range used only 15 per cent. of the fuel, and wasted about 85 per cent.

The following table is given in the report to show a sort of balance sheet of the heat put into a kitchen range :—

[1] Fuel Research Board: Report No. 4, "Tests on Ranges and Cooking Appliances," by A. H. Barker.

	Per cent.
Heat communicated to food, say	3
Heat communicated to hot-water supply	7
Loss in the air of the kitchen	30
Absorbed in the brickwork	35
Lost in flue gases, say	25
	100

It must not be thought that the losses shown here are inevitable. The results of the tests referred to indicate that a range could be designed which, for the same work, would use less than one-half the fuel required by those of the usual construction.

Independent Hot-Water Supply

The ordinary domestic boiler for the supply of hot water has an efficiency of about 40 to 45 per cent., and it is difficult to increase this very much, owing to the small size of the boiler and the necessity for simplicity of construction as well as convenience for cleaning, and so on; but the efficiency of the independent boiler is a very great improvement on that of the boilers found in ordinary kitchen ranges.

The figures for efficiency are valuable, but it must not be supposed that all the heat lost could by any reasonable means be utilised, although there is room for great improvement. The intermittent use of fires, carelessness, and the like make a large amount of waste unavoidable. Much could be done by careful insulation of hot-water pipes and storage systems, as the actual amount of heat required is small if it is not allowed to escape and go to waste. It is, for example, quite possible to provide a hot-water supply for a small household by the consumption of about 5 lb. of fuel per day.

To permit an easy comparison between methods available in England for domestic heating and cooking, a synopsis of the relative advantages and disadvantages of the different methods has been prepared, and this is set out below :—

Methods of Heating Rooms Compared

Open Coal Fire

Advantages.—1. Bright and cheerful, gives something to poke.

2. Heats by radiation, and does not unduly raise the air temperature or lower the relative humidity.

3. The chimney draught is a good ventilator, and keeps the room air in movement.

Disadvantages.—1. Requires constant attention and stoking.

2. Very dirty. The coal and ashes cause much dirt in the house, and the smoke pollutes the air outside.

3. Requires a considerable time from lighting before any appreciable heat is given off.

4. When not required, the fire cannot be put out immediately. This results in unnecessary consumption of fuel.

5. A store of fuel is necessary, with the accompanying troubles of dirt, carrying coal, provision of cellars, ordering coal, etc.

Closed Anthracite or Coke Stoves

Advantages.—1. May be arranged to burn night and day, and thus save relighting each morning ; by keeping the stove burning slowly at night the house is kept warm and dry.

2. Require less attention than open coal grates.

3. Economical ; even when burning night and day cost less than open coal grates.

4. Less dust than with open fires.

5. No smoke.

Disadvantages.—1. Heat chiefly by convection, *i.e.*, currents of hot air. The air itself is, therefore, heated, and may become unpleasantly dry, because its relative humidity is lowered.

2. The draught is usually much less than with open grates, and thus closed stoves, as usually set, do not ventilate the rooms so well.

3. A considerable amount of intelligence is required to

manage slow combustion stoves, while the danger resulting from mismanagement is greater than with open grates.

4. Owing to the reduced air supply, a large amount of poisonous carbon monoxide gas is produced in the stove, and the escape of this into the room has to be carefully guarded against. Such stoves are not suitable unless where there is free ventilation and intelligent supervision.

5. A store of fuel is necessary.

Open Gas Fires with Flues

Advantages.—1. No store of fuel required.

2. No dirt from ashes or carrying coal.

3. No smoke.

4. Can be lighted when required, and extinguished when not required, without the delay and useless consumption of fuel which results in the case of coal fires.

5. Heat chiefly by radiation, as with open fires.

6. Ventilate the room well when properly fitted to do so.

7. Economical if used properly.

8. No trouble in lighting.

Disadvantages.—1. The cost for continuous working is two to three times that of open coal fires.

2. Are not so cheerful as coal fires ; no dancing flames nor pictures in the fire.

3. Liable to escape of fumes into the room unless carefully fitted and of correct construction, which is by no means always the case.

Central Heating by Hot Water or Steam "Radiators"

Advantages.—1. No coal or ash in the house, and, therefore, no dirt produced except in the boiler chamber.

2. Keeps house very dry.

3. Makes no smoke, if boilers are heated by coke.

4. Very economical, costing for fuel about one-half as much as open coal fires.

Disadvantages.—1. Heats by convection, as do closed stoves ; air dried and heated,

2. Does not ventilate : on the contrary, owing to the loss of heat resulting from good ventilation, there is a tendency to economise fuel at the expense of fresh air and health.

3. Makes considerable deposits of dirt on walls over radiator.

Methods of Cooking, Heating Water, etc.

Kitchen Ranges

The ordinary kitchen range fitted with a boiler for heating water is by no means economical. It must not be imagined that the water is heated by heat which would otherwise go to waste ; this is not so. Not only is it necessary to burn extra coal to heat the boiler, but it would be hard to devise a more inefficient way of applying the heat so produced.

The ordinary coal-burning kitchen range is a most wasteful and dirty piece of apparatus. Usually it does not work well with coke alone, and, therefore, the ordinary smoky coal is burnt. Also, the amount of coal which can be, and is, consumed in kitchen ranges is amazing. Makers will doubtless tell us that all this is not true, but we should not be deceived ; ranges are simply devourers of coal. Whether required for cooking or not, the fire must be kept going, and so there is continual waste.

Gas Cookers

The great advantages of gas cookers are :—

1. No dirt, coal or ashes.
2. No smoke or soot.
3. Need not be kept burning when not required, and are instantly ready when wanted.
4. Economical if used with care, owing to (3).
5. Easy to control the heat.

Perhaps the chief drawbacks are that they do not heat the kitchen nor provide hot water for baths, washing, etc.

Some of the disadvantages of coal fires would be removed if low-temperature coke were used instead of raw coal.

CHAPTER XV

THE REMEDY—SOLID FUEL AND DOMESTIC SMOKE

The following table is of interest as showing the total output of coal from the mines in the United Kingdom, and the way in which the consumption is divided over the various industries.

This table is taken from the Report of "The Coal Conservation Committee," 1918.

Coal Raised and Consumed in the United Kingdom

Estimated for 1914

	Tons.
Total output of mines	287,430,473
Reserved for home consumption	189,092,369

Subdivision of Home Consumption

Estimated for 1913

Railways	15,000,000
Coasting steamers	2,500,000
Factories	60,000,000
Mines	20,500,000
Iron and steel industries	31,000,000
Other metals and minerals	1,250,000
Brick works, potteries, glass works, and chemical works	5,750,000
Gas works	18,000,000
Domestic	35,000,000
Total	189,000,000

The figures refer to the year 1913, and there is little doubt that the consumption has increased considerably since then; they need only be taken as an approximation to the present consumption.

In respect of the extent to which gas has been found serviceable in place of coal, the following figures have been

kindly provided by Mr. E. W. L. Nicol, engineer and fuel expert to the London Coke Committee :—

The amount of coal used by the gas industries in London is 4,600,000 tons a year, in addition to some 17,000,000 gallons of mineral oil. This quantity of fuel is distributed to consumers in the form of gas, 353,000,000 therms, and coke, 2,250,000 tons ; while the coal consumed in the process of carbonisation amounts to about 15 per cent. of the total carbonised.

The ratio of coal so treated to the total coal used in London exceeds 22 per cent., whereas for the country as a whole it is only about 6 per cent., which shows that the contribution of the gas works towards the mitigation of smoke is proportionally much greater in London than in provincial cities.

Low-Temperature Coke

We now revert to the question of low-temperature coke as a solution of the smoke problem. It has been already mentioned in Chapter XIV.

Those who desire to make a closer study of the problem may be referred to a comprehensive book by Dr. C. N. Lander (Director of Fuel Research) and R. F. McKay, entitled "Low-Temperature Carbonisation." The problem is approached from a purely scientific aspect in order that conclusions may be arrived at which are unbiassed by commercial considerations.

Low-Temperature Carbonisation

When coal is carbonised in suitable retorts without access of air, gases are given off and liquids are condensed which provide fuel oil, motor spirit, lubricants, as well as other useful products. The solid left behind, or coke, has certain properties depending on the temperature of carbonisation. If this is kept below about 600° to 650° C., a coke is obtained which ignites easily and burns in an open grate with a clear, bright, smokeless fire. This is called semi-coke, or "low-temperature coke." On the other hand, if the temperature of carbonisation is raised to about 850° C., a denser and

harder coke is obtained which is of very little use for open grates. This is the ordinary gas coke.

There are many processes of carbonisation at low temperature, which differ in mechanical details rather than in fundamental principle. The originator of each method naturally feels and claims that it is the best. It is of the greatest value to the country that we have now a Fuel Research Department, to which the duty of examining and reporting upon the different systems can be entrusted.

The position at present does not permit of any final answer being given to the question whether it will be possible to solve the smoke problem by setting up a great industry capable of handling many millions of tons of coal on sound economic lines. Each ton of bituminous coal when carbonised yields 70 to 80 per cent. of low-temperature coke. Thus something like 50,000,000 tons of coal must be treated if the coke is to replace the 40,000,000 tons of coal used annually in domestic fires. It is evident that so large a quantity cannot be supplied from colliery waste.

The results of trials indicate that from each ton of dry bituminous coal carbonised the following quantity of products may be obtained :—

Tars	About 170 lb., or 7·5 per cent.
Motor spirit	2·5 gallons.
Rich gas of a calorific value of about 800 to 1,000 B.Th.U. . . .	3,500 cubic feet.
Smokeless semi-coke . . .	70 to 80 per cent.

It has already been shown (see p. 245), according to Dr. Fishenden's tests [1] in 1920–21, that this semi-coke burns in an open grate with a higher radiant efficiency than coal or the gas coke of high-temperature carbonisation. This was also proved by tests made by Dr. Owens of "Coalite" and "Charco" in 1909–10; the radiant efficiency of either proved greater than a fire of bituminous coal.

We cannot do better than reproduce here the conclusions of Dr. Lander and Mr. McKay on the requirements which a

[1] Fuel Research Board, Tech. Paper No. 3.

good smokeless fuel for use in this country should satisfy. These are given as follows :—

1. It must have been previously treated for the recovery of valuable by-products from the raw fuel, and so rendered smokeless.

2. It must contain sufficient volatile matter, say, 7 to 10 per cent., or be of such structure as to be easily kindled and kept alight in open fireplaces as at present constructed, *i.e.*, it should require very little draught for combustion.

3. It must have a relatively low ash content, partly to prevent an undue reduction in its calorific value and partly to reduce the dust resultant upon combustion when burnt in household fires, and to reduce clinkering troubles when burned in boiler furnaces.

4. It must not be so friable as to break easily during handling and transport.

5. It must be compact, but not of such a structure that the ash formed during combustion covers the surface of the fuel in such a manner as to hinder combustion or to mask radiation.

6. Its price must be sufficiently low, so that, when the other advantages are taken into account, it will attract purchasers away from bituminous coals. If the coke be sold in the form of briquettes, the advantages of uniformity and coherence should be taken into account when considering the economic value of the briquettes.

There are many processes by which a good smokeless semi-coke can be produced, but this is not the whole of the problem. It will be seen from the six conditions above enumerated that it is by no means easy to attain a full solution. The technical part of the problem is inextricably associated with the commercial side. It is useless to solve the technical part unless the process can be operated under the conditions obtaining in the country as a sound financial proposition. Thus we find that the real difficulties lie in the necessary association of technical with financial soundness.

The economic side of the problem is very difficult to solve, and too many claims have been made in the past based too much on the desire to convince the investing public.

We may now look at a few of the points affecting the economic or financial side of the question :—

1. Price of Fuel.—It may be taken for granted that unless the price of the new fuel is a little less than that of raw coal, or at least the cost of heating by it is a little less, people will not be inclined to use it of their own accord.

2. Price of Oils.—The price obtainable for the oils produced

during the process is likely to be determined by the competition of the great oil companies, and may be forced down to an uneconomic level, although special markets may be developed for the new oils in time. In making an estimate, the Fuel Research Board have taken the price of oil as 5*d*. per gallon, the price of crude fuel oil.

3. Rich Gas.—A market for the rich gas obtained must be found. It may contain 40 to 50 per cent. of saturated hydrocarbons and methane, and would be very valuable for enriching gas of low thermal value.

The Fuel Research Board took a tentative value of 4*d*. per therm for this gas, but while this may be a fair estimate of value, it is another matter to provide the market unless the gas companies co-operate.

The results obtained by any calculations on the subject of the future of low-temperature coke must depend upon whether it is proposed to operate in a comparatively small way on the waste products of collieries or whether the substitution of such a fuel for all the domestic coal now used is envisaged. The first might prove a very sound financial proposition, while the second might show a totally different result, depending on the price of the raw coal to be used This aspect must not be lost sight of, as it is desirable to avoid false impressions of the future possibilities.

An unbiassed consideration of the possibilities indicates that there is no great probability of low temperature coke taking the place of coal on any great scale unless the economic outlook is modified by some form of protection, or people are so convinced of the evils of smoke that they are prepared to pay a little more for a smokeless than for a smoky fuel. This result might, of course, be expedited by Parliamentary action aimed towards the abolition or reduction of smoke.

There are a few points worth special consideration in this connection. affecting as they do the prospects of semi-coke as a domestic fuel :—

Ash.—Owing to the economic advantages to companies making semi-coke which arise from the use of waste products of the collieries, it is only natural that there should be an effort to use the fine powdered waste of coal, as it can be bought cheaply. It is, however, unfortunate that this fine coal contains an abnormal proportion of ash, more than the large lumps, and proportionately this may be still

further increased when the coal is carbonised, since the 70 to 80 per cent. of coke produced contains all the ash of the original coal.

The problem of the ash has, therefore, to be tackled, as even when raw coal is used instead of waste the ash in the coke will be increased. It may be that this can be overcome by some process of washing or by froth-flotation of the coal before treatment, but it cannot be neglected, as excessive ash in a fuel for domestic use is very objectionable. If we buy a ton of coal containing 10 per cent. of ash, we really get only 90 per cent. of combustible or useful fuel; if the ash is raised to 15 or 20 per cent., the value of the fuel is correspondingly reduced, although the price per ton may not be altered.

Again, the presence of much ash aggravates the domestic problem. It makes the fuel dusty, and, therefore, very dirty in domestic fires, while in industrial furnaces the trouble from clinker is increased.

Friability.—If the new fuel is too easily broken, this will result in the production of large quantities of dust or powder during transport and handling, with corresponding loss to the user.

Structure.—Recent researches [1] have shown that the structure of coke has a great influence on its combustion. Coke consists of a blown up or spongy mass, the matrix having been blown into bubbles in its plastic state by the gases volatilised during the carbonisation of the coal. It has been found that the porosity of the cell walls separating individual air spaces has a great influence on the ease with which the coke burns. This is one of the points which calls for further investigation, as it may have a great influence on the value of the fuel produced.

Recent Methods of Carbonisation at Low Temperature

During the past ten or fifteen years many methods have been devised for carbonising coal at low temperatures.

[1] Sutcliffe and Evans; *Journal of the Society of Chemical Industry*, Vol. 41, 1922, p. 196.

Fundamentally they all aim at the same thing, and the differences are not so much in principle as in mechanical detail or construction. In all a retort of some form is used in which the coal to be carbonised is heated, and similarly there is some provision for the removal of the volatilised products and of the coke left behind. One of the fundamental difficulties is to secure the rapid transmission of heat to the interior of the mass of coal, and a great deal of ingenuity has been exercised in getting over it. We find, therefore, that many methods aim at keeping the coal in the retort in comparatively thin layers, varying from ½ inch to about 3 inches. Naturally, the thinner the layer of fuel the more rapid is the heating, and the more the operation of carbonising is speeded up.

The majority of the methods aim at a continuous passage of the fuel through the retort, while a few are intermittent in their action. Again, the method of applying the heat to the coal is varied. In some processes the retort is heated externally; any sort of fuel may be used for the purpose, whichever is most convenient. In others the heat is applied internally, as by passing heated gases through the coal; in other processes both internal and external heating are combined.

We do not propose to describe in detail all these different processes, but reference may be made to a few typical methods.

The Coalite Process.—This was devised originally by Mr. T. Parker, and the retorts were tapered vertical cast iron chambers cast in nests and externally heated to about 450° or 500° C. Later on, firebrick retorts were used, rectangular in section and heated in zones varying from 450° C. at the bottom to about 1,000° C. at the top. An experimental plant on a large scale was erected at Barugh, Barnsley, in which the retorts were built of firebrick, vertical and externally heated. They are of the intermittent type and have a special arrangement of iron plates hung inside about 3½ inches from the side walls, with a space between. The plates are collapsible and perforated. The charge is fed into the space between the plates and the walls, while the part

between the plates is connected to the exhauster for the removal of the gas. In order that the coke may be more easily removed, special arrangements are provided for moving the plates away from the walls. Under each retort is a cooling chamber, which is water-jacketed ; in this the coke is cooled, while the heat is recovered in the water and used for steam generation. The retorts are heated externally by gas.

The Nottingham Corporation have arranged with the Low-Temperature Carbonisation Company to take the gas made by a plant erected by this company in conjunction with the Digby Colliery Company. The plant is to treat 1,000 tons of coal per day and produce 250,000 tons of smokeless fuel per annum.

The Maclaurin Process.—This is a continuous process, and devised by Mr. R. Maclaurin. The Glasgow Corporation have recently erected a plant at Dalmarnock Gas Works on this principle in order to produce smokeless fuel and to ascertain if the gas can be economically used for boiler firing. In its latest form the Maclaurin retort is somewhat on the lines of a gas producer. It is square in section, and air blasts enter through the walls, as well as through a partition wall, at a sufficient height above the bottom for the space below to act as a cooling chamber. The coal to be carbonised is fed in at the top, passed through a zone above the air blasts where partial coking goes on, and the coke, settling by gravity, is discharged through hoppers at the bottom. Through the doors of these steam is admitted, which, passing upwards, cools the coke and passes on to the combustion zone. The gases are drawn off at the top from a special annular space surrounding a condensing chamber. The peculiarity of this process is that it may, if desired, be so run as completely to gasify the coal ; or, on the other hand, to produce a smokeless fuel. One retort holds about 30 tons.

The installation at Glasgow is to comprise five units, each treating 20 tons of coal per day. Tests made at Grangemouth showed that about 55 per cent. of smokeless fuel was obtained from Scottish coal having 6 to 10 per cent. of moisture and 33 to 35 per cent. of volatile matter. The Glasgow plant is

the first instance in which a gas undertaking has become a producer of smokeless semi-coke on a large scale, an experiment which will be watched with great interest.

Caracristi Process.—A remarkable process has been adopted in the United States of America by the Ford Company. In it roughly powdered coal in a layer $\frac{1}{2}$ inch thick on a metal conveyor is caused to pass along the surface of a bath of molten lead. It is claimed that complete carbonisation results from a five minutes' exposure. The retort may be up to 50 feet long, and the lead is heated by gas. The coke resulting from this is not delivered in a form suitable for domestic fuel, but can be pulverised for use in steam raising. The process is continuous.

Fisher Process.—A method used by the Midland Coal Products, Ltd., aims at using poor-quality coal, such as a non-coking small slack. The slack is washed to reduce its ash, briquetted, and then passed through vertical retorts by gravity. The temperature is raised to about 1,000° C., and the product contains about 1 to 2 per cent. of volatile matter, but is said to burn freely.

Fusion System.—In this system a peculiar retort is used of tubular form, arranged horizontally and revolved slowly. It may consist of a single tube or a double tube, one being inside the other. In the latter case coal is fed into the central tube, passes to the other end, and back through the annular space between the two tubes. If a single tube is used, the coal passes straight through. The coal must first be pulverised to about three-eighths of an inch diameter. With a double tube the outer is externally heated, while the inner tube receives its heat internally through the other. Thus the temperature can be very gradually raised as the coal passes along. A special feature of this retort is a loose breaker or star-wheel inside the central tube, which strikes the coal as the tube revolves, breaking it loose if it tends to adhere.

Freeman Multiple Retort.—The retort consists of a number of cast-iron chambers, one above the other, and is only suitable for non-caking coal. The coal is fed to the top chamber, falls on a rotating plate, where it is spread by ploughs into a thin layer, and also pushed off the edge. It then passes

through a central hole to the next chamber, where the same process is repeated, and so on. The temperature of the top chamber is kept at about 120° C., and in succeeding chambers it is raised until in the fifth or sixth it reaches 455° or 485° C. The underlying idea in this is to get a fractional distillation. An experimental plant has been erected at Willesden with a capacity of about 10 tons per day. The coke produced is powdered or broken, and, therefore, not suited for domestic fires unless briquetted. It can, however, be used as pulverised fuel.

These are only a few of the processes which have been or are in operation, and doubtless, after sufficient trial, there will be a tendency towards unification of method, but this is not likely to occur until the demand for smokeless fuel is sufficiently great to bring about a rapid development of low temperature carbonisation.

CHAPTER XVI

THE REMEDY—INDUSTRIAL SMOKE

It is not intended in this chapter to go into the details of each particular furnace and discuss their relative merits from the point of view of smoke prevention, but rather to consider general principles for avoiding smoke, since all furnaces for the combustion of fuel must fulfil certain fundamental conditions if they are to be successful in the prevention of smoke.

General Principles Governing Smoke Prevention

The word "prevention" is used advisedly, since it must be realised that, while it is possible to burn potentially smoky coal without emitting smoke, it is almost impossible to prevent the emission of the carbonaceous or sooty variety of smoke if it is allowed to form in the first instance. A distinction should be drawn between smoke prevention and smoke combustion. While it is possible to prevent the formation of smoke in the first instance, it is extremely difficult to burn the smoke when once it has been formed. The reason for this will appear when we consider the principles governing the complete combustion of fuel. This, of course, does not apply to the tarry smoke containing the condensed vapours of tar which are easily combustible.

Ignition Temperature.—Fuels require to have their temperature raised to a certain point before they will commence to burn; hence kindling wood has to be used in order to light a fire. The temperature at which combustion begins is called the "ignition temperature." One of the most important things in the combustion of fuel regarded from the point of view of smoke prevention is its ignition temperature, or, as it is sometimes called, the ignition point. For this reason a table is given below showing the temperatures to

which the respective fuels must be raised before they will burn in ordinary air, and, conversely, these are the temperatures which must be kept up if combustion is to be carried on ; in other words, if the temperature falls below the limits given in the table, combustion will cease or will be incomplete. This is a highly important point, as later on it will be seen that the chief cause of smoke is the quenching or cooling of gases and vapours which are in the process of combustion.

Table of Ignition Temperatures

Highly bituminous gas coal	370° C.
Ordinary bituminous coal	400°–450° C.
Welsh steam coal	470° C.
Anthracite	500° C.
(Hydrogen H)	580°–590° C.
Carbon monoxide	644°–658° C.
Methane, or marsh gas (CH_4)	650°–750° C.
Ethane (CH_2).(CH_3)	520°–630° C.
Ethylene (CH_2).(CH_2)	542°–547° C.
Acetylene (C_2H_2)	406°–440° C.

The object of this table is to show that there are definite limits to the temperature at which combustion will take place, and if combustion has started, as, for example, in the flame of burning gases over the top of a fire, and if the flame is cooled down below the ignition temperature of the gases or compounds which are burning, it will be quenched, combustion will be arrested, and smoke will be produced. As most of the volatile products of combustion of coal are hydrocarbons, the effect of arresting combustion is to produce soot or solid hydrocarbon residues. The arrest of combustion or its failure to commence may be due to a variety of causes, the commonest cause being cooling below the necessary temperature. Smoke may result from such opposite conditions as the admission of too much air or the admission of too little air.

When a charge of fresh coal is fed on to an incandescent bed of fuel, the first result is the distillation of the volatile matter from the coal, and it is during this process that smoke is produced if the volatilised gases and vapours are not completely burnt. It is evident, therefore, that at this stage

of combustion the supply of air must be carefully adjusted so that there is not enough to produce cooling of the gases, but not too little to provide sufficient oxygen for combustion.

The various causes which bring about an incorrect adjustment of the air supply and a consequent formation of smoke will be considered later.

Supply of Oxygen.—We have to rely upon the air for the supply of oxygen for combustion, and for the present purpose it may be regarded as composed of a mixture of two gases—oxygen and nitrogen—in the proportion of 21 per cent. oxygen to 79 per cent. nitrogen by volume, or 23 per cent. oxygen to 77 per cent. nitrogen by weight. To provide 1 lb. of oxygen we must, therefore, supply about 4 lb. of air.

The chief volatile gases given off by bituminous coal during the first stages of combustion are methane or marsh gas, ethane or olefiant gas, and acetylene ; all are hydrocarbons, and with perfect combustion should be burnt to water (H_2O) and carbon dioxide (CO_2). This requires a suitable proportion of oxygen. For example, marsh gas burns thus : $CH_4 + 4O = CO_2 + 2H_2O$, but with insufficient oxygen you may have $CH_4 + 2O = C + 2H_2O$, that is, solid carbon is produced.

It is not sufficient to provide enough oxygen to burn hydrocarbons unless the other conditions are also fulfilled, and these are that the oxygen must be brought into intimate contact with the gases to be burnt ; in other words, the air supply and the volatilised gases and vapours must be thoroughly mixed ; also, as already pointed out, the temperature must be maintained above a certain limit.

Any gas which burns with a luminous flame, such as that of a candle, may be assumed to be a potential smoke producer ; the luminosity of the flame is due partly to the incandescent particles of solid matter derived from the initial splitting up of the hydrocarbon by the heat of the flame. These luminous particles are carried along with the burning gas, and they pass out of the flame either unconsumed, if conditions for complete combustion are not satisfied, or they may be entirely burnt up before leaving the flame.

We see this very clearly in an ordinary candle flame.

There is a central core of unburnt gas surrounded by a luminous envelope of burning gas, and that in turn is surrounded by what may be called the zone of complete combustion, where the bright luminous particles are finally burnt up. We often see a candle smoking, and this simply means that the zone of complete combustion has been penetrated at the top by escaping unburnt soot. In this case, of course, the flame has to obtain its air from the outside. There is no preliminary mixing; if, however, the air could be thoroughly mixed with the gas before burning, the flame would not be luminous. In the case of ordinary coal gas, the old-fashioned bat's-wing burner produced a luminous flame and derived the oxygen for combustion from outside the flame. In the Bunsen burner air is mixed with the gas before burning, with the result that we get a non-luminous flame.

Certain gases, such as hydrogen, burn with a flame which, while very hot, gives little or no light, but the reason is evident; hydrogen does not produce any solid matter even when combustion is incomplete.

We have seen already that an essential condition for smoke production is that the gas or vapour which is burnt should be capable of producing solid particles as a product of incomplete combustion.

In the light of what we have now considered, let us look at the stages of combustion when a charge of bituminous coal is thrown upon the furnace.

Stage 1.—The heat of the incandescent fuel distils off the gas from the coal; liquid hydrocarbons or tars are also given off, and both burn with bright luminous flames. The volatilised tars form a yellowish smoke composed of innumerable particles suspended in the gases. These products of the volatile part of the coal burst into flame over the top of the fire if the temperature and air supply are suitable, and if combustion is complete we have nothing produced but carbon dioxide and water, but if it is incomplete, soot results.

Stage 2.—When the volatile part of the fuel is driven off, the solid coke is left on the grate, and this burns from the surface in an incandescent mass producing no smoke. We have thus two stages of combustion; first, the volatilisation

or distillation of the tars and gases—the smoke-producing stage—then the incandescent combustion of the resulting coke, or the smokeless stage.

Remembering now that it is from the volatile part of the fuel that smoke results, it is evident that coal with a high percentage of volatile matter produces the most smoke, and, at the other end of the scale, anthracite, which has practically no volatile matter, produces no smoke.

The smoke-producing coal is called bituminous coal. It contains no bitumen, and the name is, therefore, somewhat misleading, but any coal containing over 18 or 20 per cent. of volatile matter is termed bituminous. The approximate composition of such coal is as follows :—

	Per cent.
Fixed carbon	52–84
Volatile matter	12–48
Ash	2–10
Sulphur	1– 3

These coals may carry from 6 to 10 per cent. of water. They are somewhat lighter than anthracite and have a specific gravity from 1·2 to 1·5, that of anthracite being 1·3 to 1·8. It is with the bituminous coals that we are particularly concerned in considering the question of smoke prevention.

We have seen now that the most important conditions to be fulfilled if smoke is to be avoided are that a sufficient quantity of air must be supplied to burn the volatile products of the coal, but that it must not be so great as to cool the burning products below their ignition point : also that the air must be properly mixed with the volatile products and the proper temperature maintained. These are the fundamental necessities for smoke prevention, and we may now proceed to consider in more detail the ordinary furnace and how it fulfils or fails to fulfil the necessary conditions.

The Furnace

General Description.—So far as smoke prevention is concerned, the general principles governing the construction of furnaces for burning coal are the same whatever the function

of the furnace may be. In the following description the furnace is, therefore, discussed on somewhat general lines, since it is unnecessary to give in detail each particular type. We may take the ordinary boiler furnace as typical, and this should embody certain essential parts, which may be summarised as follows :—

(1) The grate on which the fuel is burnt.
(2) A door or other means of admitting fresh fuel to the grate.
(3) A combustion chamber or space over or beyond the fire in which the volatile products are to be burned.
(4) The chimney, with its system of flues to carry off the products of combustion.
(5) The ash pit, to receive ash from the grate.

The Grate.—This must have certain dimensions, which depend on the rate at which coal is to be consumed. Its function is to support the fuel and admit air for combustion as well as to provide for removal of the ash.

When the draught is generated by a high chimney, it seldom exceeds 1 inch of water column, and is more usually one half to three quarters of an inch. With such a draught 15 to 20 lb. of coal may be burnt per square foot of grate area per hour. If forced or induced draught be used, this rate may rise to 45 or 85 lb. When the rate of fuel consumption is kept within certain limits depending on the particular arrangements, and if the furnace is suitably designed, smoke can be almost entirely prevented. If, however, the furnace has to be forced and made to burn more than it is designed for, incomplete combustion results, with the production of smoke. Thus the relation between the grate area and the duty of the furnace is of great importance from our present point of view. This becomes evident when we remember that a certain quantity of air is necessary for each pound of fuel burnt, and the supply of air depends upon—

(*a*) The draught or difference of pressure causing air to enter the furnace ; and
(*b*) The area of opening through which this air has to gain admission.

The Door.—Provision for stoking must be made, and its

nature plays an important part. A furnace consumes fuel continuously, and it should, therefore, strictly speaking, be fed continuously. When an ordinary furnace door is provided for hand stoking, two injurious results follow: the coal is supplied at intervals, and often irregularly, thus unnecessarily cooling the fire, while during stoking large volumes of cold air are drawn into the furnace at a time when there is no need for extra air, and in such quantity as to cool further the combustion chamber. Both these factors act in the same direction to increase smoke production. It is advantageous to open the door slightly after stoking, to admit enough air to burn the volatile parts of the fuel distilled off at this stage. Usually a grid is provided in the door which serves the same purpose, and it may be made automatic in its operation so that the act of closing the door opens the grid, while, with the aid of a suitable dash-pot, the grid gradually closes itself a suitable time after stoking. This is a very useful addition, and serves to reduce smoke greatly, while, being automatic, it does not depend for its action on the stoker's attention.

Combustion Chamber.—This is one of the most important parts of the furnace. The large volumes of volatile matter given off during the first stages after stoking require space in which to burn. Not only so, but it must be a space kept so hot that the temperature does not fall below the ignition points of the gases. If too small, the volatile products escape unburnt or partially burnt, and there is consequently a waste of fuel.

The combustion chamber is usually over or behind the furnace, and is lined with fire brick to conserve the heat. Its temperature depends to a great extent on the quantity of air admitted to the furnace. For example, from 1 lb. of carbon burnt in a minimum of air we get 3·67 lb. of carbon dioxide and 8·9 lb. of nitrogen, or altogether 12·57 lb. of combustion products; these will have a specific heat of 0·236, while the heat produced by the carbon will be 14·544 B.Th.U., and this has to heat the products, *i.e.*, the 12·57 lb.; the resulting temperature will, therefore, be 4,900° F. (2,704° C.).

If now we suppose that twice the minimum theoretical

quantity of air be admitted, we shall find that the temperature of the products falls to 2,400° F. (1,315° C.). The quantity of air admitted is thus of profound importance. Carbon ceases to burn if the temperature falls below 700° C. or 1,300° F.; hence the need of keeping the combustion chamber well above this limit.

If the chamber is so designed that the burning gases come in contact, with the boiler plates, for example, they are very liable to be quenched. The boiler plates must always be much below the ignition temperature, as they are approximately at the same temperature as the steam inside. If the pressure in the boiler be 200 lb. per square inch, the temperature of the steam will be 388° F. (196° C.). The hydrocarbon gases and vapour given off from coal have ignition temperatures not very different from that of carbon (see table on p. 264), and they will be promptly extinguished if, while burning, the flame strikes boiler plates at 388° F. For this reason the combustion chamber should be lined with fire-brick, and of such size that the volatile matter may completely burn out before the flames reach boiler tubes or plates.

The cooling of the flames causes copious formation of soot, which appears as smoke or partly as a deposit upon the plates and tubes, impeding the flow of heat into the boiler.

There are certain objections to a fire-brick lining. It is a bad heat conductor, and if applied round the furnace of a Cornish or Lancashire boiler, would hinder the transfer of heat from the fire to the boiler: hence we cannot always get the ideal conditions in practice. In addition to this drawback, it reduces the size of the furnace and calls for occasional renewal. When, however, the reduction in size can be compensated and the fire-brick does not cut off the available heating surface of a boiler, there is no doubt about its advantages.

The following table gives a rough idea of the temperature of a furnace from the appearances of the fire:—

Appearance of Fire.	Temperature. Deg. C.	Deg. F.
Red. Just visible	475	887
„ Dull	550	1,022
„ Dull cherry	626	1,157

Appearance of Fire.	Temperature. Deg. C.	Deg. F.
Red. Full cherry . . .	700 ..	1,202
,, Light	850 ..	1,562
Yellow. Full	1,000 ..	1,832
,, Light . . .	1,050 ..	1,922
White	1,150 ..	2,120

The Chimney.—The function of the chimney may be summarised as follows :—

(1) To produce draught when mechanical means are not adopted.

(2) To carry away the products of combustion.

(3) To discharge those products at such a height as to minimise the probability of their becoming a nuisance.

A chimney is not the most economical way of producing draught for installations exceeding certain dimensions. In order to produce a draught by means of a chimney it is essential that a certain amount of heat should be given to the flue gases and allowed to escape up the chimney. This may amount to 15 or 20 per cent. of the total heat of fuel burnt, whereas the actual power absorbed in producing the draught itself may be under 1 per cent. By using mechanical means to produce a draught, that is, a power-driven fan, the heat which would otherwise be lost in the flue gases may be used—for example, to heat the ingoing air to the furnace—or at least a large proportion of it may be so used, and thus a greater economy obtained.

In this connection it should be remembered that one of the functions of the chimney is to deliver the products of combustion sufficiently high up in the air to prevent their becoming a nuisance to people in the neighbourhood, and when mechanical draught is used there is a tendency to reduce the height of the chimney, since the only object of height then is that just described. This is a point of some importance, and has to be taken into account when the question of mechanical draught is considered.

With reference to the amount of air admitted to a furnace, although it is now recognised that the best efficiency can be got when there is little or no smoke to be seen from the top

of the chimney, it does not follow that the admission of sufficient air to dilute the smoke so as to make it apparently of very low density is advisable, as this may result in very inefficient working of the furnace. On the other hand, when dense smoke is emitted, it implies considerable waste of fuel in soot, but even more in unburnt gases, as there is a tendency with insufficient air for carbon to burn incompletely to carbon monoxide rather than to the dioxide, resulting in great waste of heat: also, the hydrocarbon gases and tars escape incompletely burnt. Unburnt carbon monoxide may also be carried away from a clear fire when it is very thick and an excess of air is allowed in over the top, sufficient to sweep away the carbon monoxide before it has time to burn. All this means, shortly, that there is a correct amount of air which will give a minimum of smoke with maximum efficiency. It is not necessary to labour the point further, since engineers are well aware that smoke from correctly-designed boiler furnaces which are not overworked is unnecessary except in very small quantity.

One precaution should always be taken, that is, some provision should be made by which the fireman is able to see the top of the chimney. This cannot always be done directly, but it should always be possible to arrange mirrors so that the fireman can get a view of the top of the chimney. He will then be able to see whether his air supply is being adjusted properly and to keep the smoke emission under proper control.

The following table gives the rate of combustion attainable[1] with different intensities of draught and height of chimneys:

Draught in inches of water.	Rate of combustion of fuel lb. per hour per square foot of grate.	Height of chimney above grate, in feet.
0·182	10	25
0·364	16	50
0·137	17	60
0·512	18	70
0·583	19	80
0·657	20	90
0·729	22	100
0·802	24	110

[1] "Steam Boiler Construction," Walter S. Hutton, London, 1891.

Draught in inches of water.	Rate of combustion of fuel lb. per hour per square foot of grate.	Height of chimney above grate, in feet.
0·875	27	120
0·948	30	130
1·029	34	140
1·095	40	150
1·313	50	180
1·459	60	200
1·641	70	225
1·825	80	250
2·189	90	300
2·553	112	400

Factors Governing the Emission of Smoke

Having now considered the main elements of the ordinary furnace, let us deal with some of the most important factors in its working which govern smoke emission.

Stoking.—It has already been mentioned that, since a furnace consumes coal continuously, it should, properly speaking, be fed continuously, but this is impossible by means of hand stoking. Again, the opening of the furnace door admits cold air, which cools the combustion chamber and makes for inefficiency and smoke production. This can be to some extent avoided by partially closing the damper between the furnace and the chimney when the door is opened. As to intermittent firing, the evil of this cannot be done away with entirely as long as hand stoking is retained, but it can be minimised by feeding the fuel at short intervals and in small quantities.

The following instructions for hand stoking embody the main points to be kept in mind :—

1. Fire small charges at frequent intervals. It has been shown that the fresh fuel abstracts heat from the fire ; hence, to keep the loss of heat small, the charge must be small.

2. Break coal into lumps about 2 inches diameter, a little smaller than a man's fist. This prevents a large lump lying at one spot and cooling the fire, and also making it of uneven depth.

3. Either—

(*a*) Spread the fuel lightly over the whole fire.

(*b*) Spread it along one side of the furnace, alternating the sides each charge ; or

(*c*) Feed it on to dead plate and push it over fire when gases have distilled off.

4. Open the grid in furnace door, if there is one, for about a minute after stoking, then close. If there is no grid, open door itself a little for about a minute after stoking. This admits air over the fire to burn the gases given off from the fresh coal.

5. Keep the fire of even depth and without bare spots; not too thick a fire, or the air flow through the fuel is impeded too much.

6. Keep the steam pressure steady and do not force the boiler; if more fuel is fed to the furnace than it can deal with properly smoke and loss result.

Mechanical Stoking

By the use of mechanical stokers many of the disadvantages of hand stoking can be done away with. The supply of fuel can be made continuous, while the opening of the fire door becomes unnecessary. In addition, by adopting the coking type, smoke can be practically eliminated.

We may now turn to a short consideration of mechanical stokers as smoke abaters. There are three chief types of mechanical stokers:—

(*a*) The coking stoker, in which fuel is fed on to the front part of the furnace and coked there, the gases being burnt over the incandescent fuel further back.

(*b*) The underfeed, in which the fuel is fed under the incandescent fire, and the gases have to pass through it.

(*c*) The sprinkling stoker, in which the coal is spread evenly over the whole surface.

The coking stoker, is a good smoke preventer if not forced. The feed is continuous and no opening of a furnace door is necessary as in hand stoking. If forced, the mass of unburnt fuel extends back into the furnace further than it ought, the incandescent part is correspondingly contracted, and thus it soon ceases to act efficiently as a smoke preventer.

Under proper conditions the underfeed stoker is a good appliance for preventing smoke, but it is by no means always effective in that respect.

For smoke prevention the sprinkler stoker is not so good as either of the other two, but, combined with proper arrangements for the admission of air over the fire and for mixing it well with the burning gases, the chimney may be practically smokeless.

In fact, any type of stoker may be smoky or smokeless, according as it is fitted and worked intelligently or otherwise.

Special Devices and Furnaces

Remembering the great importance of supplying air over the fire at the right time, we are not surprised to find that there are many appliances on the market for doing this; some have air jets playing over the fire, some have induced jets blown through the front of the furnace; others supply the secondary air through a split bridge or a bridge with suitable ducts and openings; others, again, admit air from the ash pit through the dead plate.

All these methods are more or less effective, according to whether the air supply is so arranged as properly to mix with the gases after the smoke has been formed.

There is a type of furnace, not often seen in this country, in which the air supply is drawn downwards through the fuel instead of up. In this case the gases are forced to pass through the incandescent fuel on the grate, coal being fed to the top of the fire in the ordinary way. It is fairly effective in preventing smoke, but it is not a very convenient form of furnace.

Several furnaces for burning pulverised fuel have been tried, and some with great success. The coal is ground to a fine powder and blown into the furnace mixed with a jet or jets of air; it burns like a gas, and if properly designed no smoke need result. In practice, however, powdered fuel furnaces have often failed, and the finely-ground coal is sometimes discharged in the draught, causing a worse nuisance than smoke; this difficulty has, however, been overcome in the more modern types.

CHAPTER XVII

THE REMEDY—ADMINISTRATIVE ACTION

Administrative remedies for the smoke problem have been the subject of many Acts of Parliament, and still more inquiries. The most recent official contribution to the subject is the final report of Lord Newton's Committee, which is dated December 6th, 1921. An interim report dated June 1st, 1920, is incorporated in the final report. The report recites the sequence of attempts to deal with the smoke problem by legislation, beginning with a petition from Londoners in 1648, an abortive Bill in the reign of Charles II., and an unproductive committee in 1819. Lord Newton's Committee originated in 1914, in the assurance of the President of the Local Government Board, Sir (then Mr.) Herbert Samuel, that, in consideration of the withdrawal of a Smoke Abatement Bill introduced into the House of Lords by Lord Newton in that session, he "would appoint, as early as possible, a strong Departmental Committee, on which all interests concerned would be represented, to examine the present state of the law and its administration, and to make proposals for consideration before Parliament definitely committed itself to any further amendment of the law." The late Mr. Russell Rea, M.P., was appointed Chairman of the original Committee, which took a certain amount of evidence. It was reconstituted by Dr. Addison, Minister of Health, in January, 1920, and reported to his successor, Sir Alfred Mond, Bart. The members of the Committee were Lord Newton (Chairman), Captain Sir I. Hamilton Benn, Professor J. B. Cohen, Mr. W. S. Curphey, Sir John Lithiby, Mr. J. S. MacCabe, Dame Louise Gilbert Samuel, Mr. E. D. Simon, Bailie W. B. Smith, and Sir Frederick Willis. We quote the summary of recommendations which forms Part XII. of the Committee's report.

Summary of Recommendations

"We have summarised below the various recommendations "which we have made in the body of this report. It will be "noted that we have also recapitulated, under their appro- "priate headings, the recommendations already put forward "in an interim report."

(a) With regard to Industrial Smoke

"1. That the Minister of Health should be given clearly defined power to compel or act in place of any defaulting authority which refuses to perform its duty in administering the law with regard to smoke. (Paragraph 97.)"

"2. That the general legal obligation on all manufacturers, users and occupiers of any business premises or processes, engines or plant of any description whatever should be to use the best practicable means, having regard to all the circumstances of the case, for avoiding the pollution of the air by smoke, grit or any other noxious emissions; that the same law should also apply to all Government establishments and all rail and road locomotives and motor cars, of whatever weight or type, and to steamers on rivers, estuaries and lakes."

"It must be clearly understood that questions of cost must be taken into account in determining what is practicable. (Paragraphs 80–81.)"

"3. That the Minister of Health should be empowered to fix standards from time to time, and in any case in which the emission exceeds the standard so fixed, the onus of proof that the manufacturer is using the best practicable means should be on the manufacturer. (Paragraphs 82–86.)"

"4. That the *duty* of enforcing the law with regard to pollution of the air by smoke should be transferred from the local sanitary authorities in whose jurisdiction it now rests to the county authorities, *i.e.*, the Councils of Counties and County Boroughs; minor authorities should still have *power* to take proceedings if they so desire. (Paragraph 93.)"

"5. That the Minister of Health should be empowered to constitute Joint Committees consisting of two or more Councils in cases where it appears to him that this course would lead to the better administration of the law with regard to smoke in any given area. (Paragraph 95.)"

"6. That the Minister of Health should assign to one or more competent officers the duty of advising and assisting local authorities and manufacturers with regard to difficult smoke problems; these officers should report annually on the steps which are being taken and the progress which has been made in the suppression of avoidable smoke. (Paragraph 96.)"

"7. That the law should enable much larger fines to be imposed than at present. (Paragraph 90.)"

" 8. That legislation should be introduced at an early date with a view to consolidating in one measure the various existing statutory provisions with regard to the pollution of the air by smoke, and providing for their amendment where necessary to give effect to the above recommendations. (Paragraph 91.) "

(b) With regard to Domestic Smoke

" 9. That the Central Housing Authority should decline to sanction any housing scheme submitted by a local authority or public utility society unless specific provision is made in the plans for the adoption of smokeless methods for supplying the required heat as suggested in our Interim Report. The only exception to this rule should be when the Central Authority are fully satisfied that the adoption of such methods is impracticable. (See Section VII., Recommendations, of the Interim Report, Appendix B.) "

" 10. That the Government should encourage the co-ordination and extension of research into domestic heating generally. This is a matter of great importance in view of the many outstanding problems which demand inquiry. (See Section VII., Recommendations, of the Interim Report, Appendix B.) "

" 11. That local authorities should be empowered to make bye-laws requiring the provision of smokeless heating arrangements in new buildings other than private dwelling-houses, such, for example, as hotels, clubs, offices and the like. (Paragraph 62.) "

(c) General

" 12. That Gas and Electricity Undertakers should be given every facility and encouragement to increase and cheapen the supply of gas and electricity, and that the practice at present followed by some municipal authorities of overcharging for gas and electricity in order to allocate the profits thus accruing to the relief of the rates should be discontinued. (See Section VIII., Recommendations, of the Interim Report, Appendix B.) "

(d) With regard to Noxious Vapours

" 13. That the Alkali, &c., Works Regulation Act, 1906, should be amended so as to apply generally to all manufactures from which noxious vapours might come. (Paragraph 106.) "

" 14. That a list of such noxious vapours should be included in the Act, and the Minister of Health should be empowered to add to this list from time to time other noxious vapours, after due inquiry. (Paragraph 110.) "

" 15. That a general obligation should be placed on every manufacturer of using the best practicable means for preventing the escape of noxious or offensive vapours. (Paragraph 107.) "

" 16. That the present system of registration should be continued,

and the Minister of Health should be empowered to require the registration of classes of works not at present required to be registered. (Paragraph 109.)"

"17. That the Minister of Health should be empowered to fix standards from time to time after due public inquiry with regard to noxious vapours in cases where he finds it desirable; and these standards should have the same legal force as those which we recommend with regard to smoke. (Paragraph 108.)"

It will be noticed that the line of progress indicated in the report is to continue the policy of making the production of too much smoke illegal, and to strengthen and otherwise improve the means of enforcing penalties against the offenders. At the same time, in order to deal with domestic smoke, it is recommended that the Central Housing Authority should not sanction housing schemes submitted by public bodies which do not include the adoption of smokeless methods of heating, unless the authority thinks such methods impracticable, and local authorities are to be empowered to require the provision of smokeless heating in domestic establishments that are not private dwelling-houses.

Progress by Encouragement Instead of Penalty

Some twenty years ago, having occasion to review the question of the treatment of smoke, we became impressed with the fact that the method of dealing with the question by legislative penalties for excessive smoke appeals more naturally to lawyers and lawgivers than to the other classes who still form the majority of mankind, and that, in the corresponding treatment of the sewage problem in days now gone by, the plan which proved so splendidly successful was for the local authorities to provide at the expense of the community an alternative to the crude methods of sewage disposal which used to make large towns the centres of all sorts of infectious disorders.

After considering some details of the analogy between the sewage problem and the smoke problem, it appeared that the smoke problem was in certain respects the easier one, because there were means for accomplishing the objects of combustion without production of smoke, but no known means of carrying on domestic affairs without the production

of sewage. It was, therefore, possible to appeal to the members of the community with an offer of consideration in return for renouncing the customary right to produce smoke instead of providing the means for removing it.

The interval that has elapsed since that suggestion was published has only confirmed the opinion as to its being a practical method of approaching a practical solution of the problem. It is not necessary to have the same consideration in every town. Those communities who think a smoky atmosphere is an advantage may postpone action until they see what can be done. Without, therefore, remitting any of the proposals for penalising the offenders who become conspicuous, we propose to put forward an example of the application of the method of encouragement in the particular instance of South Kensington as being a neighbourhood in which domestic smoke is a prominent part of the common nuisance.

The recital of this case will serve to set out, first, the actual problem for the neighbourhood as determined by the methods of investigation which have been described in the preceding chapters, and, secondly, the method by which the remedy might be achieved so far as domestic smoke is concerned. We should then look to Parliament for further assistance in dealing with the remaining sources of atmospheric pollution.

By way of considering a mode of procedure we propose to take a definite example. In South Kensington, in the course of an average month, 579 grammes ($1\frac{1}{4}$ lb.) of solid matter fall upon a 10-metre square (about 100 square yards) —about a pint of loose dirt. The total amount is made up of 16 grammes tar, 198 grammes solid carbonaceous matter other than tar, 365 grammes of other insoluble solids, and dissolved in the rain water which accumulates with the deposit are 202 grammes of volatile salts and 340 grammes of non-volatile soluble salts, giving a total amount of solid 1.117 grammes per 10-metre square—a quart of loose solid dirt.

Floating in the atmosphere of Westminster we find $\frac{1}{10}$ mg. per cubic metre in an average night, $\frac{1}{2}$ mg. per cubic metre

on an average summer day, and $\frac{3}{4}$ mg. per cubic metre on an average winter day, 2 mg. per cubic metre on a foggy day.

During an ordinary clear day we may find in a cubic centimetre of the atmosphere 300 solid particles, and on a foggy day 40,000 such particles.

These differences between an average day and an average night, and between a foggy day and an ordinary clear day, are caused by smoke, and can be prevented by administrative action which has the effect of substituting smokeless fuel for smoky fuel. The limit of impurity ought not to be greater than $\frac{1}{10}$ mg. per cubic metre. The administrative problem is to devise means by which the present smoke "owners" will be induced to use only smokeless fuel.

We are all personally conscious of the exceptional impurity of the atmosphere by the smarting of our eyes and the annoyance to our breathing, by the collection of dirt in our nostrils, on our clothing, on curtains and furniture, and by the more permanent record in the deterioration of buildings and metals. On special days, such as Tuesday, November 19th, 1922, London paid the penalty by living in darkness the whole day.

We know, further, that in the West End of London two-thirds of the total impurity in the atmosphere must be attributed to domestic smoke, leaving one-third to be accounted for by industrial smoke.

The remedy, which has been tried in various forms for a century at least, is to mark down the chimneys which appear to be special sinners and to move the magistracy to penalise their owners by a suitable fine on the ground that the chimneys have been emitting "black" smoke. The moderate smoker, whether domestic or industrial, incurs no responsibility.

Public opinion has often been vocal after a day of black darkness, but only a few enthusiasts regard the making of no smoke as a duty which they owe to the community, irrespective of legal penalties.

There is very good reason for the apathy of the individual citizen; he is perfectly justified in saying to himself that if "I spend my time and money in providing myself with

apparatus for warming and cooking which make no smoke, I shall be not one whit better off myself, the advantage will be entirely my neighbours'. I shall still go on breathing their smoke and clearing up their dirt; so long as they give me their smoke I am entitled to give them mine in return."

Three things are therefore necessary in order to make an effective start in removing the evil, which is universally acknowledged in words, and almost universally ignored in action.

These three things are :—

(1) The remedy must be applicable to domestic smoke as well as to industrial smoke.

(2) The public in general must be consciously interested in the success of the scheme.

(3) The remedy must make some direct appeal to the individual smoke owner.

At present the individual smoke owner has a grievance if he is singled out for any measure of coercion. The provision of suitable apparatus in a house already built and used involves some outlay. The introduction of new bye-laws imposing disabilities upon new houses which do not apply to old houses gives the old houses a preferential right to foul the air, which may have some weight in the competition between them.

There is another difficulty about general coercive legislation. Houses are mostly owned by landlords and occupied by tenants; the tenants make the smoke by using the apparatus which the landlord or his predecessor has provided. The landlord already finds himself so hampered by legislation that he cannot discharge his existing liabilities, and another capital charge without compensation would be resisted by all the powers that landlords possess. So, equally, the compensation of an enhanced rent would be resisted by all the powers that tenants possess.

Rebate on Cleansing Rate for Smokeless Premises

These points would all be met by a law based on the principle that it is to the interest of the community that there should be no smoke, although it may not be to the

interest of any individual member of the community here and now. Effect may be given to this principle by a law permitting the local authority to allow a rebate from the cleansing rate for houses, new or old, that are so arranged that no smoke is emitted from them. It would be for the owner or occupier to satisfy the local authority that he was entitled to the rebate for the ensuing half year in the first instance (not the current half year), and thereafter "during good behaviour." If the rebate were sufficiently attractive, the visit of an inspector of the local authority would be welcomed instead of being resisted.

We need not contemplate any elaborate administrative machinery for the inspection of dwellings. The natural process would be for appliances and fuels to be scheduled as approved by the rating authority. A form could be circulated with the half-yearly demand for rates, to be filled up by the ratepayer as follows :—

"I claim to be allowed the rebate of 3*d.* in the £ on the cleansing rate for the ensuing half-year on the ground that all the appliances which I use for cooking and heating are approved as producing no smoke, viz. :—

1. For cooking . . .	Gas stove only, supplied by the local Gas Company.
2. For domestic water heating .	Coke boiler and three electric kettles.
3. For destruction of refuse .	Coke stove of No. 2.
4. For central heating . .	Potterton gas boiler, No. 1523.
5. For local heating . . .	6 gas fires, 2 electric radiators, 1 open fire.
6. Fuel used for open fire . .	Low temperature coke supplied by Smith & Co. on January 22nd.

And I undertake that the appliances shall be so used that no smoke will be emitted from my premises beyond that which results from the necessary burning of refuse.

(*Signed*) "A. B."

The form, duly filled up, would be sent in when the half-year's rate was paid, and when stamped as approved would authorise the rebate from the next half-year's demand. At the same time, the local authority would know how much had to be allowed in the borough accounts on account of rebate, and could adjust the gross rate accordingly.

Smoke coming from a chimney of an approved dwelling would be evidence of non-compliance with the undertaking. There would be many voluntary assistant inspectors, because any infringement of the undertaking would be a fraud upon the others who made a similar undertaking. Public opinion tends to be very severe in such cases.

In contrast with this scheme we may consider some other proposals which have been made to meet the case. Mr. Percy Alden, in the December number of the *Contemporary Review*, suggests the imposition of a tax on coal sufficient to induce the consumer to abstain from using it. We are already so heavily taxed that additional taxation for any purpose whatever will be odious for some time to come. Moreover, taxes have to be imposed by Parliament year by year in the Finance Act. One of the fundamental principles of finance is that taxes shall be directed towards raising revenue, and for that purpose alone. A tax which would be held to have been completely successful if not one penny was produced thereby is not a tax in the sense in which the word is understood in British finance.

Moreover, the project of taxing the whole country for the sake of the atmosphere of the towns is sure to be regarded as inequitable. If raw coal is penalised, we might still have briquettes or other substitutes which may escape the appellation of "raw coal" just as leaves or other garden rubbish would do.

A tax is evidently less suitable than a rate as an avenue of approach to the administrative remedy of the smoke problem, because it is of general as compared with local application.

The policy of those who would remedy the smoke problem should be to concentrate their attention upon one locality; London is perhaps the best for the purpose, but Manchester or Birmingham or Glasgow would do almost equally well. It is unnecessary to postpone an effort to remedy smoke in London until a proposal has been found which meets with the approval of the steelmakers of Sheffield. If any one of the places mentioned finds a remedy which is effective in the local circumstances, we may be sure that the other localities

will not be long in adopting its provisions. Therefore, local provisions are preferable to national provisions.

Another suggestion is to prohibit the use of raw coal. Prohibiting is a difficult undertaking; what is prohibited must be precisely defined, and anything not included is allowed. The exclusion of anthracite, for example, as raw coal would be unjust. Consequently we may get a fuel which is no better than raw coal, but escapes prohibition because it was not thought of. Moreover, the sale of coal in London and in the country generally is a very large industry, and its simple suppression in favour of gas or electricity would not be tolerated. We have, therefore, to consider the possibility of the general substitution of a smokeless coal for raw coal on a very large scale, and at a price which would enable it to compete with coal. That has been pronounced by the Fuel Research Board to be not impossible in the future, and the question is whether anything can be done to encourage progress in that direction and to mitigate the smoke nuisance while the final stages of the economic problem of converting coal into smokeless fuel are being solved. The rebate on the cleansing rate would be an immediate incentive to progress in that direction, because with smokeless coal nothing need be spent on new appliances, and if the ratepayer so desired, the rebate could go towards paying for smokeless fuel while its cost is still higher than smoke fuel. In the meantime those people who preferred to change their system of heating would be enabled to do so.

The question may be raised as to how to prevent the fraud of a ratepayer undertaking to use smokeless fuel and, after claiming the rebate, actually using raw coal instead. In this connection it may be remembered that the onus of proof lies with the ratepayer who asks for relief on the ground of his service to the community. He may, therefore, be required to produce a receipt for a supply of the smokeless fuel that he is going to burn, or to give any other form of guarantee. His more honest neighbours would not fail to notice his smoky chimneys, as now we impotently notice a chimney on fire; it is, in fact, difficult to hide the products of smoky fuel, and default in the undertaking not to use it

would be easily detected. In any case, it is much easier than the direct application of a rule of prohibition of raw coal. In order to enforce the prohibition as against the householder elaborate regulations would be necessary, with some penal provisions that might lead to complicated litigation.

As an example of the proposed rebate for smokeless premises we will take the case of the borough of Kensington. From the demand for rates for a half year it appears that the rateable value of the borough was £2,548,333 per annum ; the rates for the half year were assessed to produce £755,856, of which £56,063 (5·19*d.* in the pound) was levied as cleansing rate for the removal of house refuse, sweeping and cleansing the streets, etc.[1]

Let us suppose that the Borough Council (having been duly authorised so to do) decreed that the cleansing rate on any house or tenement that was so arranged and so managed as to make no smoke should be reduced by 3*d.* in the half year, 6*d.* per year.

The rebate on a tenement of rateable value £100 a year would amount to £2 10*s.* a year. That might be capitalised at 6 per cent. at £40. Such a sum would probably suffice for the necessary landlord's alterations in a large number of cases. The calculation would hold good so long as the landlord in question was the only one who took advantage of it. It would, therefore, be to his advantage to act quickly.

To provide for the case in which the tenant pays the rates, but the landlord has to do the preliminary work necessary for carrying out the scheme, let it be agreed that of the 3*d.* rebate 2*d.* goes to the landlord, leaving 1*d.* for possible increased cost of fuel to the tenant.

Of course the cost of cleansing the borough has still to be paid and rates collected for that purpose. Suppose that on the adoption of such a measure one in twenty of the tenements of the borough could make good their claims to the rebate ; it would be necessary to increase the cleansing rate to make up the deficiency. The full rate would, there-

[1] The figures for the half year to 30th September, 1925, are £606,787 and £53,043 (4·96*d.* in the pound).

fore, become at once 5·45*d.* in the pound instead of 5·19*d.*, not important for the moment : but if in consequence of the encouragement thus given a fresh twentieth established claims each year, then in twenty years there would be no advantage to be got by making any particular house smokeless, but all would have become so, and in the course of the development the smoke owners would always be making up the deficiency caused by the allowance to the no-smoke owners.

It is important that the consideration should be large enough to make the proposition attractive to individual owners, and it might be desirable to differentiate in favour of the smaller holdings, as used to be done in the case of the inhabited house duty, because the capital cost of rendering a house smokeless is not proportional to its rateable value. A sliding scale might be made of 3*d.* in the pound for rateable value of £200 or over, increasing by 1 per cent. for every pound less than £200, that is, to 6*d.* in the pound for £100, and 9*d.* for £50. That is rather elaborate, but rather more effective than a flat rate.

This regulation might apply to factories and works as well as domestic establishments, although the penalties for black smoke or any other voluminous smoke should still be retained. When the general public were making arrangements for abolishing their own smoke they would take care that the worst culprits did not go unpunished as sometimes they do now.

The occasional annoyance from the burning of rubbish in a neighbour's garden raises a question which requires careful consideration when general action is taken in the direction of abolishing the production of smoke : that is, the disposal of house refuse other than ashes. In some towns it has been the rule that the householder must consume his own animal and vegetable refuse. It is not altogether wholesome in any case to allow that kind of refuse to accumulate, and some means of disposing of it should be found. Combustion is the best in many ways, and the smoke from the burning is not nearly so noxious as that from raw coal. Perhaps centralised destruction may now be preferred but no surgery

and no lawyer's office, indeed no professional office, not even a Government office, could be regarded as entirely sufficient without some sort of incinerator. One of the advantages of an open fire, or kitchen range, is the possibility of its use in case of necessity as an incinerator. The question therefore of a domestic 'destructor' remains a part of the general problem of the smoke of great cities. If means of incineration could be found at reasonable cost, the burden of the dustmen's carts might be lightened.

In support of this conclusion we need go no farther than the following legend quoted from the dustmen's cart of a progressive municipality in August, 1925:

CITY OF BIRMINGHAM
BURN YOUR REFUSE. REDUCE YOUR RATES
OH5242

Adjustment of rates in special circumstances is no innovation. Municipal authorities already allow a reduction in rates on small property when it is paid by the owner in bulk, because incidentally it saves the community the cost of collection. The advantage to the community of redemption from smoke is certainly quite as great as that secured by the payment of rates in bulk.

There are other examples of discrimination on account of individual circumstances of the assessment of rates or taxes. We extract a quotation from a Life of Robert Louis Stevenson: "Their house, Number 3, is at the extreme east. They, therefore, probably enjoyed the immunity from rates by which the Town Council tempted citizens to migrate from the huddled and overcrowded Old Town to the unsheltered plain across the new bridge." [1]

[1] "Life of Robert Louis Stevenson," by Rosaline Masson, p. 22.

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